COMPUTER MODELLING AND ASSESSMENT METHODOLOGY FOR THE THERMAL ENERGY PERFORMANCE ANALYSIS OF INSTITUTIONAL BUILDINGS IN NIGERIA

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ABSTRACT

Nigerian economic growth is spurred by the increasing population and the need for modern infrastructure. The energy and construction sectors are under immense pressure to meet the increasing demand for housing, educational, commercial, and health buildings and a reliable electrical power supply grid. In addition, to contribute to reducing the impact of climate change, the governmental authorities are required to develop clear and enforceable national construction codes and related building energy efficiency measures specific to the diverse climates of the country. However, there is currently little research on institutional educational building infrastructure, specifically targeting thermal comfort provision applicable to the diverse Nigerian climatic zones.

This research explored ways of improving university buildings' thermal comfort and energy performance in the hot-dry town of Birnin Kebbi (latitude 12.45°S; longitude 04.20°N), Nigeria. The research investigated two University learning buildings with mix-mode ventilation, where overheating in the indoor space is prevalent. The research identified that high solar radiation exposure, inadequate orientation below standard construction materials, and inefficient building delivery were among the parameters that contributed to thermal discomfort to occupants.

The research methodology involves both qualitative and quantitative evaluation of thermal comfort using computer modelling, which is a direct measurement of building space operating parameters of temperature and humidity and a survey of building occupants. Integrated Environmental Solutions Virtual Environment (IESVE) software was used as the main analytical tool for parametric and energy efficiency analysis. The subjective evaluation of occupants by interview and questionnaire administration through the Post Occupancy Evaluation (POE) process was carried out using ASHRAE-55 Standard guidelines to investigate and analyse the Predictive Mean Vote (PMV) and Percentage of People Dissatisfied (PPD) votes of the occupants concerning the comfort perceptions and level of satisfaction with indoor conditions across the seasons. The findings from the experimental measurement of collected data and POE investigations show that the building operates outside the recommended indoor temperature of 26°C for educational buildings. In effect, the lower and upper indoor temperatures were 27.0°C and 32.0°C, respectively, while the comfort temperature was of 29.5°C. The findings from simulations reveal that shading devices applied on the external fabric of the buildings could form an effective passive strategy for solar heat gain control, but this can compromise the daylighting level required for the learning environment.

The computer simulation shows that by implementing passive design strategies (building orientation, insulation, shading), the cooling load of the studio and classroom areas of the building can be reduced by 32% and 28%, respectively. However, the simulated daylight factor (DLF) for the two spaces was 4.6% and

1.6%, respectively, indicating that the classroom complex was below the minimum light level standard.

Furthermore, the research investigated the integration of renewable energy in the form of PV panels to generate low-carbon power to offset part of the cooling load of the building. The computer modelling shows that by integrating PV panels on the available roof area of the studio and classroom buildings, up to 127MWh and 213MWh of annual electrical power can be generated, respectively. Therefore, this study recommends that renewable energy resources by integrating PV panels to support a sustainable supply of energy to the building~~s~~ and the minimum shading standard achieved in the research should be incorporated in the Nigerian Building Code and Building Energy Efficiency document.

PUBLICATIONS

Bena, A. A., Gillott, M., & Boukhanouf, R. (2019). Review of Strategy for Assessing the Thermal Performance of Institutional Building Form in Hot Dry Climate of Nigeria. In SET Malaysia (Ed.), *18th International Conference on Sustainable Energy Technologies 20th – 22nd of August 2019, Kuala Lumpur, Malaysia– SET 2019* (pp. 1–10). SET Malaysia.

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LIST OF ACRONYMS

AC: Air Conditioning

ANSI: American National Scientific Institute

AT: Air Temperature

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

BC: Building Code

BCS: Base Case Study

BEE: Building Energy Efficiency

BEEG: Building Energy Efficiency Guidelines

BEM: Building Energy Model

BIM: Building Information Modelling

BIPV: Building Integrated Photovoltaic

CAD: Computer-Aided Design

CFD: Computational Fluid Dynamics

CIBSE: Chartered Institution of Building Services Engineers

CO2: Carbon Dioxide

CT: Comfort Temperature

DBT: Dry Bulb Temperature

DLF: Daylight Factor

DXF: Drawing Exchange

ECS: Egg Crate Shading

EQ: Environmental Quality

FUBK: Federal University Birnin Kebbi

FF: Form Factor

GDPR: General Data Protection Regulation

GUI: Graphical User Interface

HS: Horizontal Shading

HSA: Horizontal Shadow Angle

HVAC: Heating, Ventilation, and Air Conditioning

IESVE: Integrated Environmental Solution Virtual Environment

IE: Indoor Environment

IEQ: Indoor Environmental Quality

IPCC: Intergovernmental Panel on Climate Change

ISO: International Organization for Standardization

MRT: Mean Radiant Temperature

NESP: Nigerian Energy Support Programme

NNBC: Nigeria National Building Code

NOAA: National Oceanic and Atmospheric Administration

NS: No Shading

NTV: Night-Time Ventilation

NUC: National Universities Commission

NV: Naturally Ventilated

PCM: Phase Change Materials

PMV: Predicted Mean Vote

PMV: Predicted Mean Vote

POE: Post Occupancy Evaluation

POP: Pilasters of Paris

PPD: Percentage of People Dissatisfied

PV: Photovoltaic

RC: Reinforced Concrete

RH: Relative Humidity

SAA: Solar Altitude Angle

SAP: Simulation Assessment Procedure

SC: Sun Cast

SC: Shading Coefficient

SET: Standard Effective Temperature

SHGC: Solar Heat Gain Coefficient

SHGC external = solar heat gain coefficient of external shading devices
SHGC glazing = solar heat gain coefficient of the glazing
SHGC internal = solar heat gain coefficient of internal shading
SHGC total = total solar heat gain coefficient of the fenestration system

SHGF: Solar Heat Gain Factor

SPSS: Statistical Package for the Social Sciences

SRI: Solar Roof Index

TMY: Typical Metrological Year

VHSA: Vertical and Horizontal Shadow Angles

VLT: Visible Light Transmission

VS: Vertical Shading

VSA: Vertical Shadow Angle

WR = wall ratio

WWR = window-to-wall ratio

ZCH: Zero Carbon Hub

LIST OF ABBREVIATION, NOMENCLATURE, AND SYMBOLS

ΔT = temperature difference (°C)

$A_{Surface}$ = surface area (m^2)

A_{floor} = Floor area (m^2)

A_{TF}= total area (m^2)

clo = clothing insulation (unit)

ET = Effective temperature (°C)

htc = heat transfer coefficient (W/m^2K)

HSA = horizontal shading angle (deg)

M = metabolic rate (W/m^2)

pa = vapor pressure of air (kPa)

Qc = conduction heat flow rate (W)

Qe = evaporative heat flow rate (W)

Qi = Internal gains heat flow rate (W)

Qs = solar heat flow rate (W)

Qv = ventilation heat flow rate (W)

Rcl = clothing thermal insulation

R_T= Thermal Resistance (K/W)

T_{comf} = comfort temperature (°C)

Tn = neutral temperature (°C)

Tout = Mean outdoor dry bulb temperature ((°C)

To = Monthly mean of the outdoor dry-bulb temperature(°C)

U = conductance or U-value (W/m2K)

V = air velocity (m/s)

VSA = vertical shading angle (deg)

CHAPTER ONE

1. INTRODUCTION

1.1 Background of the Study

The Intergovernmental Panel on Climate Change (IPCC) in 2022 reported that the building industry is responsible for a significant portion of global electricity consumption, accounting for two-thirds of the total usage. Furthermore, this sector is the primary source of greenhouse gas emissions worldwide (IPCC, 2022). Additionally, it accounts for approximately 50% of all materials extracted from the earth's crust, 35% of all greenhouse gases produced, 40% of all water used per weight, and 40% of raw materials consumption. For the enhancement of people's well-being, global mitigation initiatives are required to be keenly focused on reducing energy usage in buildings, which can be achieved by decreasing CO_2 emissions, as stated in the Sustainable Development Goals Report. (UN, 2022).

The global climate zones have significant characteristics that affect the ability of building professionals to create sustainable designs. Researchers such as Zomorodian et al. (2016), commonly use the Köppen-Geiger climate classification to group climatic preferences and environmental parameters that impact buildings on different continents. The climate has a major impact on a building's performance in achieving energy efficiency, as noted by (Vijayan et al., 2022). However, the positive effects of climatic elements on buildings can result in an alternative reduction of thermal/energy indices and carbon footprint and provide eco-friendly, healthier, and sustainable living spaces, as stated by (Lawrence & Keime, 2016) (CIBSE, 2013).

This research concerns the case of Nigerian institutional buildings, where recently, public higher education institutions, particularly universities, have experienced rapid growth in student enrolment and infrastructural development due to government investment and the establishment of new institutions. However, many facilities are gradually deteriorating due to poor planning, design, construction, and maintenance, performance and energy efficiency (Alhassan et al., 2022; Bena et al., 2019; Ali, 2018, Hayatu et al., 2015). According to Ochedi and Taki (2019) and Olagunju (2019), energy-efficient designs and building constructions have several benefits, including protecting the environment, promoting the well-being of occupants, and reducing reliance on electricity.

The energy sector in Nigeria is dominated by fossil fuels which are used for power generation, including oil and gas (17%) and biofuels and waste (82%), with renewables accounting for a mere 0.4%. Nigeria is currently facing a significant shortage of electricity supply, with an increasing demand for air conditioning and cooling devices. Nigeria's electricity demand surpasses its supply, which remains undependable, with less than 41% of the total installed capacity, as lamented by the Nigeria Building Energy Efficiency (BEE) guidelines document (Arup, 2016) NESP, 2015). It was reported that commercial and institutional buildings consume energy mainly for cooling and lighting. Air conditioning (AC), utilises between 40-60%, lighting uses 13-37%, and office equipment consumes 12-25% of total energy (Geissler et al., 2018; NESP, 2015). This huge demand for power in buildings is difficult to avoid due to the intense solar radiation experienced year-round, making the use of air conditioning devices critical rather than a luxury. Educational institutions have also recognized the need for air conditioning to attract prospective students. However, relying on AC for thermal comfort is not sustainable in terms of energy demand for ensuring conducive thermal comfort provision in indoor environments. It is crucial to focus on the provision of natural ventilation in the design of university facilities; this approach will minimize the use of energy-reliant systems that deploy energy-intensive mechanical systems to ensure student comfort. By embracing a climate-suitable strategy, learning spaces can become ideal locations for improved productivity, as reported by (Ali, 2018).

Applications of passive and energy-efficient design approaches also allow for possible retrofitting of existing buildings in Nigeria. Tertiary institutions globally play a crucial role in providing quality education, offering spaces for learning, administration, and utilities. Therefore, these buildings must be designed and constructed to be sustainable and energy-efficient (Aghimien et al., 2018). For example, passive design and construction technology devoted comfort standards based on adaptive and predictive comfort models, which were considered reliable options by the Nigerian energy efficiency guideline document also considered by the Nigerian Energy Support Program (NESP) document (NESP, 2015, NESP, 2017). Recent studies of university learning environments in the hot, dry climate of Nigeria show that the occupants (students and staff) can adapt to a less comfortable environment when passive design techniques are implemented to mitigate climatic effects associated with overheating, particularly during the summer due to solar radiation across the climatic zones. The occupant's ability to adapt to their environment would depend on the availability of adaptive opportunities (Bello et al., 2021; Kolo and Olagunju, 2018; Said et al., 2016). Studies in passive building design and construction of institutional infrastructure that promote occupants' adaptive opportunities are required as input to the policy document building energy efficiency (BEE) (Arup, 2016). Achieving increased human performance and development of occupants of higher institutional buildings is associated with providing comfort in the indoor space; simultaneously, occupants' subjective judgment regarding their thermal environment offers an important rationale for investigating factors affecting their mental performance. A whole building simulation retrofitting upgrade of institutional buildings for improving occupants' thermal perception, Indoor Environmental Quality (IEQ), and cooling load reduction are exemplary research reviewed towards achieving minimum IEQ in similar existing buildings. These studies are on the increase due to the heightened demand for retrofitting buildings in diverse comfort modes and in different climatic zones; studies by Guevara et al., (2021), Zuhaib et al., (2018), Mishra and Ramgopal, (2014), were focused on subjective thermal sensation evaluation of students' learning spaces and in whole building measurement, simulation and retrofitting for achieving performance and energy efficiency (Irulegi et al., 2017; Barbhuiya & Barbhuiya, 2013).

Architectural studios and classrooms are critical learning spaces but differ in indoor occupancy patterns, utility functions and types of equipment. They are also distinguished by the nature of the subjects delivered to students, which influences their thoughts reported by (Bughio et al., 2020; Shrestha and Rijal, 2023). It is important to learn from research that considers how occupants in institutional buildings perceive their thermal environment for the provision of desired IEQ and the opportunities they get from adaptation to the climate.

1.1.1 Overview of Nigerian Higher Education Sector

The Nigerian government prioritised its education sector by enacting the "National Policy on Education" in the 1977 document, which was later revised in 1981 and 1990 to ensure that it aligned with the government's objectives and catered to the country's educational needs. The National Council of Education, chaired by the Federal Minister of Education and consisting of all State Commissioners of Education, coordinates political policies. The Joint Consultative Committee on Education, comprising all Federal and State Directors of Education, provides the Council with advice on funding and needs. However, recent reports indicate the need to meet the UNESCO benchmark of 26% in the education sector, (Jacob and Musa, 2020; Odigwe & Owan, 2019; Moja , 2000).

The educational system in Nigeria is administered jointly by the Federal and State Ministries of Education and Commissions. These Commissions oversee various aspects of the educational system, with the National Universities Commission (NUC) supervising all universities in the country. However, in the late 1970s and early 1980s, the higher education system grew rapidly in size, rather than in quality. Unfortunately, implementing strategies to extend the educational system for social and economic development has been challenging due to weak information systems, monitoring, limited budgets, and a lack of planning and managerial capacity, as reported by (Olutola and Olatoye, 2020; Moja, 2000).

1.1.2 Historical Development of University Infrastructure in Nigeria

According to Asojo and Jaiyeoba (2016) In the 20th century, university campuses in Europe and America were influenced by modernism, an architectural style characterised by the application of modern construction materials and elements in building construction. Still, little information exists on its integration into West African university infrastructure. The University of Ibadan, founded in 1948, ranked Nigeria's top university in the period that showcases modernist influence in its facilities. Other universities established during the period include the University of Nigeria, Nsukka, Obafemi Awolowo University, Ahmadu Bello University, and the University of Lagos. The second-generation Universities were established in 1975, including the University of Jos, University of Maiduguri, University of Sokoto, University of Calabar, University of Ilorin, and Bayero University, Kano (Mogaji, 2019). Nigeria's Constitution allowed the Federal and State Governments to establish universities. However, making this an exclusive legislative item, from 1979 to 1983, eight State universities were established in various states. In 1988, the University of Abuja was established in the Federal Capital Territory (FCT). In addition, five federal universities of technology were established in different areas, as well as universities of agriculture in Abeokuta and Makurdi. By December 1989, there were 28 universities in Nigeria, consisting of 20 Federal and eight State universities. In 2023, there are 220 approved universities in Nigeria, including 50 Federal Universities, 59 State Universities, and 111 private Universities, according to information available on the NUC websites (Mogaji, 2019; NUSSD, 2023).

1.1.3 Challenges of Building Infrastructure in Nigerian University

Many public universities in Nigeria suffer from a significant lack of necessary infrastructure for academic and non-academic services (Ogunode, 2020). These infrastructures include libraries, laboratories, lecture halls, offices, administrative buildings, hostels, roads, water supply, electricity, and internet access. The availability of these facilities is crucial for the smooth functioning of educational institutions, and their absence severely hampers it. For instance, numerous public universities in Nigeria face shortages of lecture halls, laboratories, and offices for students and academic staff. Moreover, there are not enough offices for staff, and students struggle with limited access to lecture halls and hostel accommodations. According to research by Jacob et al. (2020), physical infrastructure greatly affects students' academic performance. The inadequate facilities pose a significant threat to the effectiveness and sustainability of the educational system. Poor planning, corruption, lack of maintenance, and inadequate funding contribute to the insufficient infrastructure. A survey by the National University Commission showed that only about 30% of Nigeria's student population has adequate access to classrooms, lecture theatres, laboratories, and libraries, underscoring the alarming state of Nigeria's university infrastructure (Monday and Mallo, 2021).

1.1.4 Design Construction and Planning in Nigerian Universities

The concept of universal design across public university campuses in the country, according to Sholanke et al., (2019), is a design ideology that targets the provision of utility spaces for teaching, learning, socialisation, and research development, accommodating the accessibility and usability needs of everyone regardless of their status and background. It is recommended that Managers of academic environments provide immediate community facilities and services through efficient design and construction to satisfy the needs and expectations of every user group without any form of segregation or discrimination against any group for the desired planning and implementation of institutional campuses.

Despite the continued funding by the Nigerian government and giant boost in the provision of physical infrastructure and development, it is, however, observed that in most universities, educational facilities are overstretched, substandard, and inadequate, and many of these buildings are newly constructed and occupied often failed in performance, before reaching their targeted lifespan. Many Nigerian universities evolve through self-induced planning that constitutes barriers to achieving universal design compliance of academic buildings in universities; maintenance is a very important aspect of facilities management that requires planning because lack of maintenance leads to serious economic loss, as reported by (Ugwu et al., 2018).

According to Asojo and Jaiyeoba (2016); finding ways to improve the planning and design of university campus buildings requires a strategy and maintenance of facilities for users. Some of the common problems that hinder the achievement of having a universal design and planning and abandonment of projects in the Nigerian public university environment arose from lack of policy planning, poor monitoring and evaluation, problems in the execution of construction, handling and implementation and lack of continuation in government policies. The authors further added there is a strong indication that academic buildings adequately meet the accessibility and usability needs of all categories of users; there is a need to eliminate the identified barriers preventing universal design compliance by retrofitting the structures with inclusive design features. Existing academic buildings of public Universities in Nigeria are national treasures, facilities that require routine and periodic maintenance for sustainable growth and development, a position reported by (Jacob and Musa, 2022, Sholanke et al., 2019).

1.1.5 The Establishment of Federal University Birnin Kebbi

The Federal University Birnin Kebbi (FUBK) is one of the twelve universities established by the Administration of the then president, Dr. Goodluck Ebele Jonathan (GCFR). The president conceived that each state of the federation and the federal capital territory should have a university. The first batch of nine universities was approved to commence operation on the 16th of February 2011. Birnin Kebbi is the capital city of Kebbi State, North-western Nigeria, and is home to several higher educational institutions, including two universities, one of which is FUBK. The establishment of the Federal University, Birnin Kebbi, was deferred until 18th February 2013, alongside those of Gusau and Gashua.

The National University Commission (NUC) approved the commencement of academic activities at the university in the 2014/2015 academic session. Two faculties, Faculty of Arts, Social and Management Sciences and Faculty of Science, were approved for take-off. The University starts with a population of 507 students and 102 academic staff. The Faculty of Arts started with nine (9) departments with a population of 227 students, while the Faculty of Science had eleven (11) departments with a student population of 280. In 2015, the College of Health Science and the Faculty of Environmental Science was established. College of Health Science started with one (1) nursing and health science departments. At the same time, the Faculty of Environmental Science commenced with three (3) departments, namely, Architecture, Building and Quantity Surveying (Student Affairs Division FUBK, 2015). In 2023, two additional faculties were approved: the Faculty of Education and the Faculty of Law, bringing the number to six and increasing the population to more than 7,000 (fubk.edu.ng). The university has six (6) directorates: Academic Planning, Physical Planning, Research and Innovation, ICT Directorate, Entrepreneurship, and CSBE Directorate.

1.2 The Tropical Hot/dry Climate

Climate refers to the long-term state of the Earth's atmospheric conditions over a specific period, ranging from several decades to centuries. Climatic elements are specific to a particular location, region, or planet. These elements are temperature, humidity, wind, precipitation, and solar radiation. Climatic factors are the natural courses and circumstances that contribute to creating, maintaining, or modifying a particular environment (Hausladen et al., 2011). However, the climate of a region determines the characteristics of its vegetation and natural resources. Several methods have been developed to classify climatic boundaries or regions; the most prominent is the Köppen-Geiger system, which classifies climate into five main classes and 30 sub-types; this classification is based on monthly air temperature threshold values and precipitation seasonality (Beck et al., 2018). The first version of this classification was developed in the late 19th century and considers vegetation as a "set visible climate." This classification aims to map out distributions worldwide empirically: different regions in a similar class share common vegetation characteristics. It is still widely used today for many applications and studies conditioned on differences in climatic management, such as ecological modelling or climate change impact assessments. (Arnfield, 2023; Beck et al., 2018).

The Köppen-Geiger climate classification was considered a suitable means to group climate types into a simple but ecologically meaningful method. Climate has been recognised as the major driver of global vegetation distribution.

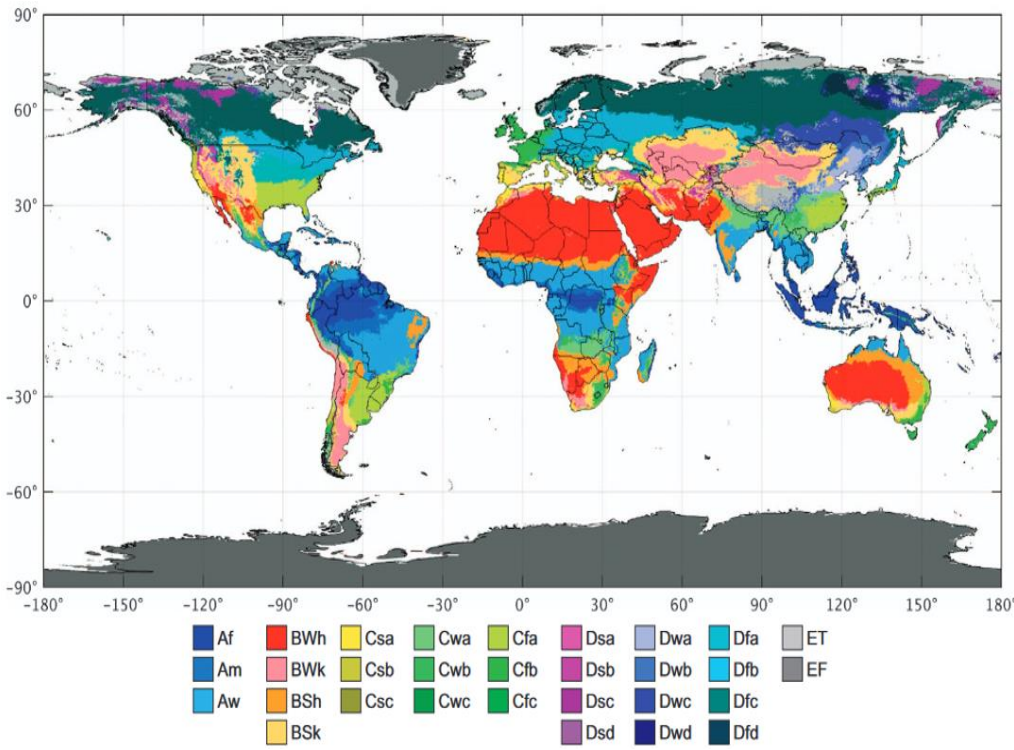


Figure 1-1 The Köppen-Geiger classification shows the present-day 1-km resolution map (1980–2016). Source: (Beck et al., 2018).

These features divided the earth's surface into climatic regions that generally coincided with world patterns of vegetation and soils (biomes). The modified Köppen-Geiger climate classification shown in Figure 1-1 is considered suitable for describing a more general world pattern of climates derived from three climatic datasets for air temperature and four climatic datasets for precipitation (Beck et al., 2018).

Table 1.1 Classification of major climatic types according to the modified Köppen-Geiger scheme. Source; (Arnfield, 2023).

Letter symbol 1st	2nd	3rd	Description	Criterion
A			Tropical	The temperature of the coolest month is 18 °C or higher.
	f		Rainforest	Precipitation in the driest month is at least 60 mm.
	m		Monsoon	Precipitation in the driest month is less than 60 mm but equal to or greater than 100 – (r/25).
	w		Savannah	Precipitation in driest months is less than 60 mm and less than 100 – (r/25).

The world is divided into five climate zones Köppen's map illustrates the different zones using various colours and shades. The zones are categorised based on the temperature and precipitation of a region. The five zones are Zone A for tropical or equatorial climates, Zone B for arid regions, Zone C for warm/mild temperate climates, Zone D for continental climates, and Zone E for polar climates. Each zone is further divided based on temperature or dryness. For instance, Zone A has three subdivisions: Zone *Af* with no dry season, Zone *Am* with a short dry season, and Zone *Aw* with a winter dry season.

Using the Köppen-Geiger-Pohl climate classification, the selected study area, Birnin Kebbi, lies within the ‘Hot/dry’ savanna climate zone, which falls within 12°.45N and 04°.20E. As illustrated in Figure 1.2. Many cities fall within this climate band on the African Map, including Egypt, Ahmedabad, Kutch, Pakistan and Solāpur, India, having a similar climate to Birnin Kebbi. Some common climatic elements showing a comparison of (temperature and humidity) is illustrated in Figure 1-3. The monthly high-temperature difference between Birnin Kebbi and Solāpur is 1-4°C, with a high margin of temperature difference in November. Across the year, there is a low-temperature difference of 0-2°C in February.

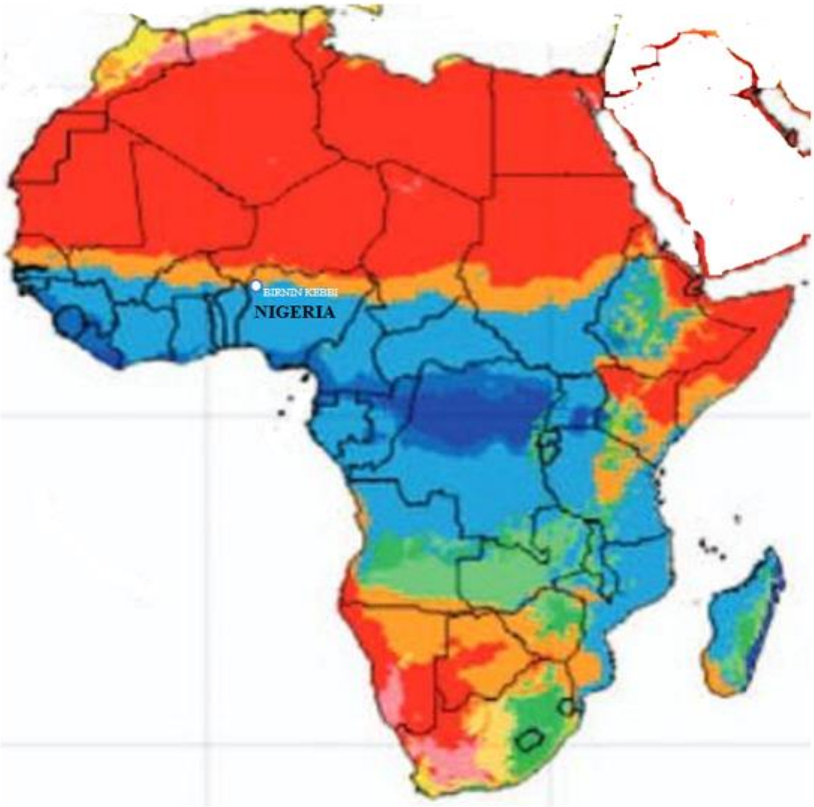


Figure 1-2 Africa Köppen-Geiger climate map, illustrating Nigeria and Birnin Kebbi (Arnfield, 2023).

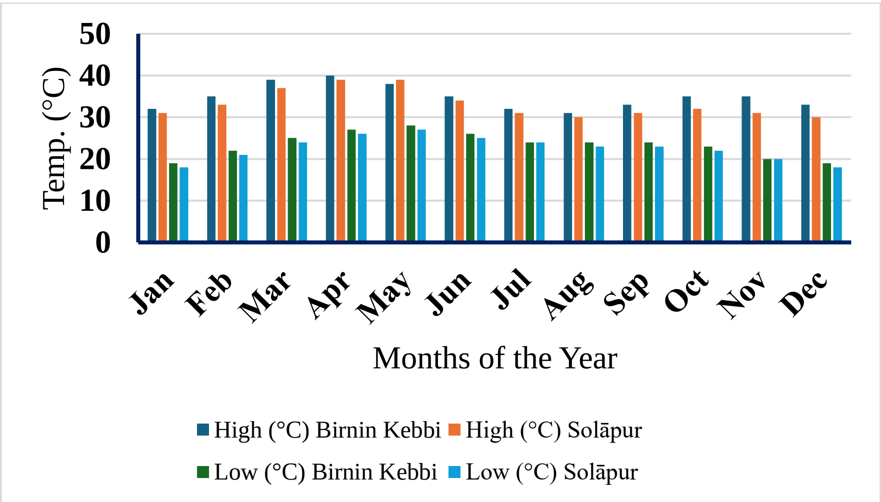


Figure 1-3 Comparison of the Average High and Low Temperature in Birnin Kebbi and Solāpur.

Figure 1.4 shows the differences in humidity between the 2-cities. The highest and lowest humidity values were recorded in September and February. A marginal difference of 1% between the two cities in the month of April and a 0.4% to 11.9% difference in humidity across the year.

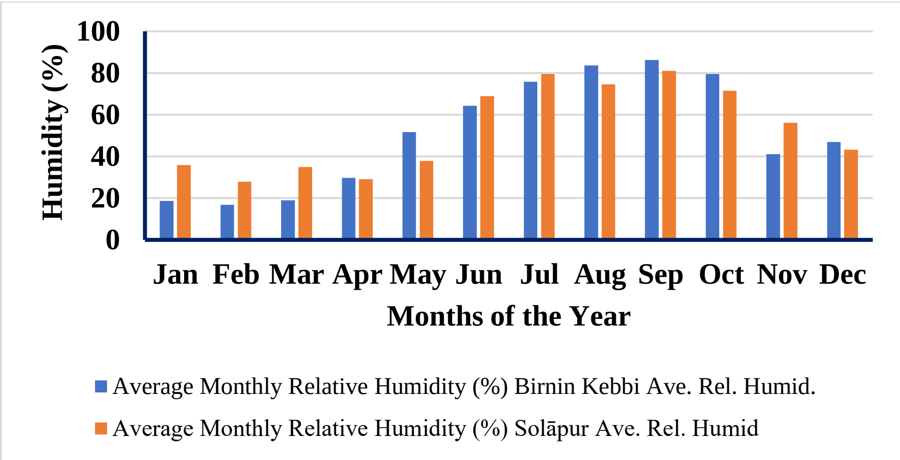


Figure 1-4 Comparison of the mean monthly Humidity in Birnin Kebbi and Solāpur.

1.3 Classification of Nigerian Climatic Zones

The bioclimatic classification of Nigerian climates recognised the characteristics of each climatic zone in determining the Architectural design approach for the regions (Mobolade and Pourvahidi, 2020).

Table 1.2 State Capital in each climate zone.

S/no.	Hot-dry zone	Temp-dry zone	Temp-dry, cold zone	Temp-humid zone	Hot-humid zone
1.	Bauchi	Abuja	Jos	Akure	Abakaliki
2.	Birnin Kebbi	Jalingo		Benin	Abeokuta
3.	Damaturu	Kaduna		Enugu	Asaba
4.	Dutse	Lafiya		Ibadan	Awka
5.	Gombe	Minna		Ilorin	Calabar
6.	Gusau			Lokoja	Ikeja
7.	Kano			Makurdi	Owerri
8.	Katsina			Osogbo	P/Harcourt
9.	Maiduguri			Ado-Ekiti	Umuahia
10	Sokoto				Uyo
11	Yola				Yenagoa

Source: (Mobolade and Pourvahidi, 2020).

Five major climatic zones are shown in Table 1.2. These include hot-dry, hot-humid, temperate-dry, temperate-humid, temperate-dry, and a dry/cool climate zone.

Figure 1.5 classification provides Architectural responses to climate change and highlights the importance of passive responses on building delivery in the climatic zones of the country. According to Mobolade and Pourvahidi, (2020), Nigerian climate has been classified previously by considering only the initial elements of the building, adaptations of the building, and vegetation of the zone, achieved through collecting the newest data from meteorological organisations neglecting a more scientific approach that considers thermal comfort methodology and using a bioclimatic charts classification for comfort zones which is significant to environmental adaptation and offers more passive guides.

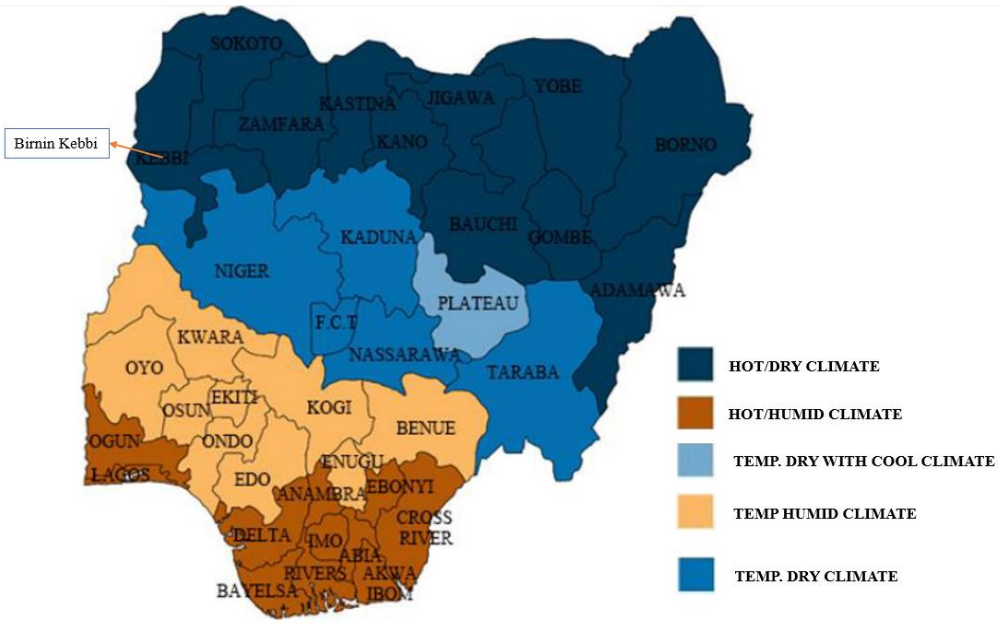


Figure 1-5 Map of Nigeria showing the classification of climatic zones. Source: (Mobolade and Pourvahidi, 2020).

1.4 Buildings in Hot/dry Climates.

The hot-dry climate of Nigeria is characterised by high temperatures during the day with a sharp drop at night and sunshine all year round, but the hours of sunlight drop a little in winter. Humidity is low, especially in the summer, which causes rapid evaporation and low rainfall (Mobolade and Pourvahidi, 2020). The advantages and characteristics of climate-adaptive building construction and design in Nigeria have been thoroughly covered in the literature (Geissler et al., 2018). Another important aspect of the climatic design was examined and recommended from the passive architecture viewpoint (Arup, 2016; Atanda and Olukoya, 2019). From a global perspective, a thorough assessment by Konis et al. (2016), that the exterior building shell is particularly important because of its direct interaction with the climate. Vethanayagam and Abu-Hijleh, (2019) explain how climate-adaptable architecture can be used to design modern structures, by submitting that, the primary purpose of building structures is to protect occupants from environmental hazards and dangerous weather.

Regardless of the architecture of the building, it was reported that Heating, Ventilation, and Air Conditioning (HVAC) systems could provide a certain indoor atmosphere for cooling, as contained in the Energy Commission of Nigeria; document ECN, (2017), in a research for investigations of offices buildings in hot climates of Nigeria. The findings further revealed that maintaining a stable 25-26°C indoor temperature (minimum in schools offices) even when the external average radiant temperature exceeds 38°C not only results in exceptionally high cooling energy demands but also creates unhealthy environments when people enter a heavily cooled building from a hot outdoor environment.

1.4.1 Overheating in Buildings

Overheating is when a building's temperature rises above what is comfortable; this means that building occupants experience uncomfortable heat produced by the indoor environment, including humidity, air movement, the building's purpose, design, management, and the occupants' attitudes, are to this discomfort. Building overheating can be caused by poor design, control, or services. The indoor operative temperatures of 25°C were recommended, and 30°C or more was identified as ‘rarely acceptable to occupants of office buildings in the UK. For educational buildings, 26°C is the minimum according to the Chartered Institute of Building Services Engineers document (CIBSE, 2013). The assumption regarding a single indoor temperature limit irrespective of outdoor conditions is no longer considered sufficient, hence the need to calculate the operative temperature for each indoor space set for evaluations based on (Nicole and Brian, 2013). Lamenting further that a building will require less energy (supplied externally) to maintain a suitable internal atmosphere more external considerations, such as temperature, site, and purpose of the building, are considered during development. Office buildings and other non-residential structures like schools and educational buildings are typically occupied during the day, resulting in higher internal gains from solar radiation, people, equipment, and lighting. To lower the heat gains and cooling loads at a reasonable index, solar gains into the building's interiors must be reduced if the design targets a thermally suitable indoor environment for the occupants (ECN, 2017).

1.4.2 Thermal Comfort in Buildings

Thermal comfort is the state of being content with the temperature in an indoor environment and is widely recognised by ASHRAE-55 (2017) and ISO-7730, (2005) ASHRAE oversees ANSI Standard-55, which provides guidelines for Thermal Environmental Conditions for Human Occupancy. The standard is updated regularly, based on Fanger's PMV index, and is recognised globally, as with EN 15251 and ISO 7730. Thermal comfort is measured by assessing the thermal sensation and thermal dissatisfaction that the occupants feel. In hot/dry climates, it is possible to assess building comfort levels using predicted mean vote PMV and predicted percentage of dissatisfaction PPD indices to express these comfort limits.

Factors like activity, clothing, and environment affect heat balance. Natural ventilation can help people feel more comfortable and reduce reliance on mechanical systems. The PPD index predicts the percentage of people who may feel uncomfortable due to being too hot or cold. It considers drafts, temperature differences between the ankles and head, and floor temperature. These factors can cause unwanted heating or cooling of a person's body, leading to local discomfort. Fanger's equation helps to relate the PMV to the predicted percentage of dissatisfaction (PPD) (Guenther, 2023). PMV is calculated using temperature, airspeed, clothing insulation, relative humidity, and mean radiative temperature. Standards recommend adjusting for speeds above 0.2m/s ASHRAE-55 (2017).

The PPD index estimates discomfort from extreme temperatures by considering factors like drafts and floor temperature. Fanger's equation uses PMV to predict dissatisfaction. PMV factors include air temperature, airspeed, clothing insulation, relative humidity, and mean radiative temperature. Adjust for airspeeds above 0.2m/s according to (Guenther, 2023, ASHRAE-55 2017).

The definition of "comfortable", however, depends on several outside variables, including a person's age, health, and other personal characteristics, as well as their activities (such as sleeping, working, and running) and their attire (e.g., light, or heavy clothes). Temperature (room temperature, surface temperature, temperature variations), air quality (humidity, CO_2 levels, oxygen levels, air velocity), and radiation are the typical factors that affect thermal comfort (from systems, materials, or solar radiation). The internal thermal conditions are undoubtedly greatly influenced by the exterior climate conditions. The metabolic heat being released in the body and its flow to the environment, are regulated to keep the internal organs, particularly the brain, at a temperature of around 37 ˚C. Heat conduction is a dynamic process of the indoor environment and changes perceived by the occupants; it is an air movement between indoors and outdoors. The body needs a mechanism for keeping the temperature of our internal organs' constant despite these changes. Mixed-mode buildings exhibit various ventilation modes, natural and controlled indoor ventilation known as 'hybrid' (mechanical ventilation) to cool/heat the interiors in some part of the year, depending on the climate. (CIBSE, 2013).

1.5 Thermal Comfort Standards and Models

Historically from the 1970s until the start of the 21st century, standards for indoor temperatures principally; BS EN ISO 7730, BSI, (2005), and ANSI/ASHRAE Standard 55; ASHRAE, (2010) were based on the PMV model outlined previously or the standard effective temperature (SET) based on the Pierce two-node model of thermal physiology; the adaptive and PMV models. Humphreys in the 1970s, De Dear & Brager, (2001) and other new studies realized that the PMV model is not appropriate, especially in naturally ventilated buildings that are in free-running mode, setting the phase for the establishment of ASHRAE-55 (2010) and BS EN-15251 including adaptive temperature limits for naturally ventilated and free-running buildings while setting the environmental standard for mechanically cooled buildings. Environmental standards are for the design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting, and acoustics, that seek to define indoor environments steady with occupant satisfaction for ensuring that energy efficiency is achieved without a rise in cost to the comfort provision, wellbeing of occupants or performance of building (CIBSE, 2013).

1.5.1 Predictive model (PMV/PPD)

The predicted mean vote (PMV) is a thermal scale that demonstrates scores from Cold (−3) to Hot (+3). It is an ISO standard. The recommended acceptable PMV range for thermal comfort from ASHRAE-55 is between −0.5 and +0.5 for an interior space. The predicted percentage of people dissatisfied (PPD) is the percentage of occupants dissatisfied with the thermal conditions. The recommended acceptable PPD range for thermal comfort from ASHRAE 55 is <10 % of persons dissatisfied. The PPD can range from 5% to 100%, depending on the calculated PMV, and these comfort values may vary depending on the occupant's location in the building. The PMV index predicts how comfortable a group of people will feel on a scale of 1 to 7 (Thorpe, 2018).

1.5.2 Adaptive comfort

Adaptive comfort models recognise behavioural and attitudinal changes in regulating the environment by occupants to stay in comfortable conditions. Comfort conditions can also be modified in the design of building elements, such as providing more windows and observing ranges of operable conditions toward natural ventilation of spaces without a mechanical cooling system. The occupants must be near sedentary and have a metabolic rate between 1.0 and 1.3 met (a met is a unit equal to 58.2 W/m^2); the energy produced per unit skin surface is of an average person seated at rest and clothing value according to (Thorpe, 2018). Adaptive temperature formulas aid in calculating SET points and comfort temperature for the occupants of buildings.

1.6 Research Aim

This research aims to assess and upgrade university buildings on thermal performance and energy efficiency in Nigeria’s hot/dry climate by recommending their sustainability. The focus is addressing the problem of overheating experienced by students in the indoor learning spaces in the summer. The research will investigate passive design strategy to evaluate the effectiveness and energy efficiency of two case study buildings, indoor learning spaces, specifically an architectural studio complex and a classroom complex, with the same height configuration but different shapes, geometry, orientations, and purpose of use,

1.7 Objectives

i. To conduct a thorough literature review and use open-source data and knowledge to study sustainable building design practices and processes of tropical hot/dry climates.

ii. To evaluate the selected case study buildings on the overheating phenomenon on climatic variables, such as temperature, humidity, carbon dioxide (CO_2) and ventilation levels, towards providing an IEQ minimum standard for occupant comfort, health, and well-being.

iii. To evaluate the case study buildings on thermal performance, IEQ, and energy efficiency through the parametric process using validated IESVE software and effective computer modelling processes.

iv. To demonstrate the retrofitting and maintenance framework for upgrading existing university buildings to achieve thermal performance and energy efficiency standards and integrate renewable energy (photovoltaic) systems into the building envelope.

v. To develop recommendations for policy and building design guidelines based on research findings toward promoting the construction of energy-efficient and environmentally sustainable university buildings in the Nigerian climate.

These objectives collectively aim to address the issues of thermal comfort, thermal performance, and energy efficiency in university buildings within a challenging climatic context, contributing to Nigeria's sustainable development of educational infrastructure.

1.8 Research Gap

Three critical areas of need for the research were identified as research gaps: building types mostly researched in the continental climatic zone, building form performance parameters, and policy requirements needed for the research. Specifically, the research addresses the following gaps in the current knowledge:

i. Limited research on indoor environmental quality (IEQ) in higher educational buildings, specifically in Nigeria's tropical hot/dry climate. Numerous studies focused on passive cooling design techniques in hot/dry climates focussing on university buildings are mostly research from the Middle East, Asia, and North Africa. Some of these studies include the works of Shanmugga and Kannamma (2022), Guevara et al (2021), Heracleous et al. (2021), Utsman et al. (2021), Tagliabue et al. (2020), Ramirez and Hamza, (2018) and Mustafa (2017), that applied objective and subjective methodologies; in survey and post-occupancy and IESVE simulation tool in the building assessment and evaluations processes. However, much indigenous research reference to the hot climate of Nigeria was on commercial office and residential buildings; the bulk of research centred mostly on energy evaluations rather than thermal comfort (Zafer and Olalekan, 2017; ECN, 2016; and Mu'azu, Abbas, 2015). There is limited research on the assessment of thermal comfort in higher educational buildings that combine multiple approaches, including software simulation; for example, research by Ali (2018) applied the objective methodology to investigate the conditions and levels of satisfaction with indoor environmental quality (IEQ) in naturally ventilated (NV) learning environments of University buildings, in hot/dry climate of Kano city of Nigeria. The study compares the results to international comfort standards' thresholds for achieving minimum indoor environmental quality (IEQ) standards. Studies by Bello et al. (2021), Nduka et al. (2021), and Sa'id et al. (2016). (2015) aimed to provide thermal comfort by reducing the energy required for cooling, using subjective evaluations and statistical analysis. Notable global studies that focused on the application of passive principles on university learning buildings that offer multi-objective methodologies and building maintenance/retrofits are reviewed to learn from the efficient strategies (Heracleous et al., 2021; Bughio et al., 2020; Tee et al., 2020; Alkhateeb and Abu-Hijleh, 2019; Merabtine et al., 2018; Zuhaib et al., 2018; Mustafa, 2017; Touloupaki and Theodosiou, 2017; Lawrence and Keime, 2016; Sarbu and Pacurar, 2015; Barbhuiya and Barbhuiya, 2013). They offer useful guidance on outstanding passive methodologies, and many utilise integrated environmental solutions (IESVE) software and related parametric simulation tools for thermal assessments and analysis. This limitation was addressed in this work by conducting a comprehensive literature review on the study to gather existing knowledge on passive cooling strategies in improving thermal comfort in indoor learning spaces, using surveys or focus group discussions to gather data on building occupants' behaviours and assess its impact on indoor environmental quality and energy efficiency.

ii. Limited research on optimising building envelope design to improve energy efficiency and thermal comfort in higher educational buildings in Nigeria. Numerous studies have been conducted globally on energy efficiency in building forms and shapes. These studies provide literature, technical approaches, methodologies, and intervention measures for different building categories in various climates. Zhang et al. (2017) achieved a maximum of 13.6% energy savings and 3.8% thermal comfort improvement in research on school buildings, where the geometric parameters with an H shape proved to be performing optimally. (2016) researched high-rise office buildings in the Malaysian climate on form/shape energy efficiency and cooling load reduction potentials by manipulating shapes in various orientations. Adinugroho and Gadi (2018) highlighted and achieved how prismatic form shapes can reduce energy consumption using passive parameters and an energy simulation tool in the tropical climate of Turkey. However, based on the earlier submission, there is a shortage of research specifically on low-rise educational buildings with complex shapes, varying geometry, and multi-functional utility spaces (offices, studios, classes) in Nigeria's climates to evaluate geometric form performance for thermal comfort provision.

iii. Lack of clear considerations for thermal comfort in the national building policy guidelines document. According to the National Energy Support Programme of Nigeria, the Building Energy Efficiency Guidelines document (BEEG) Arup, (2016), and relevant sections of Nigeria's National Building Code NNBC, (2016), lacks relevant information on thermal comfort standard compliance of institutional buildings. The document received many submissions on residential and commercial buildings but falls under guidelines on institutional education (buildings); there is a need to fill the existing gap and update the national building code for the country's environment sector. The aim is to establish guidelines, codes, and energy use index that meet required standards and strengthen professional roles in practice. The research reviewed various university building research in different global climates and facilities in varying shapes and geometry because different building types yield different results in indices of thermal comfort perception by occupant's experiences. Conducting experiments and computer simulations to evaluate the impact of form performance towards energy efficiency and thermal comfort and improving IEQ in indoor learning spaces can contribute to improving the Nigerian building policy and energy efficiency in building guidelines, particularly for low-rise education and institutional buildings.

1.9 Justification for the selection of case study building

The selection criteria for the two case study buildings were based on two factors. Firstly, the buildings were chosen because they were specifically designed for public universities by the government to meet the special space planning and design needs of faculties such as the Department of Architecture. The NUC initially mandated a policy to eventually develop these departments into full-fledged faculties of Architecture across public universities nationwide. Early studies on these buildings' performance and evaluation will provide sustainable mitigation targets. Secondly, according to initial surveys and investigations, these building models are widely constructed in public universities nationwide and are more common on campuses than any other type of building. The classroom complex has been built in four different locations on the university's permanent site campus and serves as a large-capacity learning space for various faculties. In contrast, the studio complex will be replicated within the faculty layout site based on information gathered during the survey visit. Additionally, the university management intended to construct the same type of studio model for each department offering design courses.

1.10 Research Design

Figures 1-6 illustrate the conceptual framework and structured approach of the research project, which seeks to assess the thermal performance and energy efficiency of two case study buildings in Nigeria's hot and arid climate. The framework considers the climate, research area, types of case study buildings, assessment phenomena, mixed methodology, required building maintenance/intervention levels, and necessary performance improvements. Its objective is to establish a scientific and technical strategy for addressing overheating in the buildings and ensuring optimal comfort, health, well-being, and Indoor Environmental Quality (IEQ) for the university building occupants.

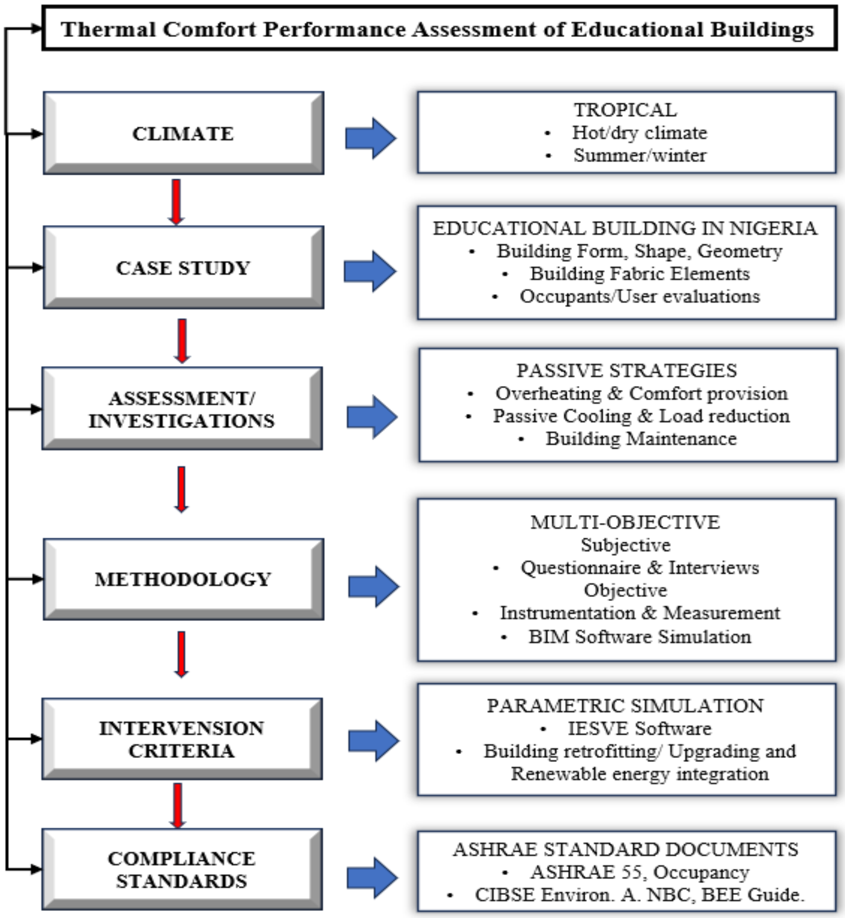


Figure 1-6 Conceptual Framework for the Thermal Comfort Assessment

1.11 Research Methodology

The thesis utilised a case study research method, conducting a one-year assessment of two educational teaching buildings at Federal University Birnin Kebbi. The research methodology combined mixed quantitative (objective) and qualitative (subjective) methods, using systematic primary and secondary data collection processes and analysis, as described by (Pruzan, 2016; Adams et al., 2014).

The qualitative research methodology, according to Ugwu and Eze (2017) and Mark et al. (2016) is a semi-structured or unstructured process frequently conducted in narrative form. It was developed to gather non-numerical data to produce insights involving feelings, ideas, or experiences, resulting in testable hypotheses. The data in this research was collected through extensive post-occupancy evaluation via questionnaire surveys, interviews, and literature reviews. The quantitative process involved field experiments and instrumentation studies in collecting weather data, thermal comfort, and other environmental parameters using sensors and data-logging instruments. This systematic process was utilised in this research, as explained by (Mark et al., 2016). The building performance analysis was performed using computer simulation and building information modelling using IES-VE software, which provided validation and building performance recommendations on thermal comfort provision, cooling load reduction, and retrofitting/maintenance development. Also, a statistical analysis was conducted, where numerical data were coded, and results were calculated and presented in tables, charts, and figures. Table 1.3 outlined how the aspects of the research methodology and their corresponding relationship with the project objectives. The overall methodology followed the ASHRAE standard guidelines, such as ASHRAE-55 (2017) and others, aiming to provide thermal comfort, indoor environmental quality, and energy efficiency in Nigeria's university buildings in tropical hot/dry climatic zones.

Table 1.3 Research methodology in relation to objectives

Research Methodology	**Objectives**	**Type of Data Collection**
1. Literature review	Passive design literature/ recommendations.	Primary/ secondary data.
2. Field Experiment	BIM design, building measurement instrumentation /data logging	Primary; Quantitative
3. Survey/ Interviews	Evaluate and analyse occupant adaptive/ predictive behaviours.	Primary; Qualitative
4. Parametric Simulation	Explore building performance through machine models.	Primary; Quantitative

1.11 Novelty of the Research

This research provides a comprehensive framework and broad scope for sustainable design, assessment, evaluation process, and enhancement of educational buildings in Nigerian hot/dry climate. The framework can be extended to other climatic zones to obtain specific results. The research's novelty contributions include: Firstly, the research provides guidelines on thermal comfort and energy performance tailored to address the challenges of higher education buildings in Nigeria's hot/dry climate. These guidelines are useful for architects, engineers, and policymakers in building design and construction in similar climatic zones. Secondly, the study highlights the importance of passive techniques for reducing cooling loads and improving Indoor Environmental Quality (IEQ) in university buildings. Natural ventilation, shading, and thermal mass are effective strategies that promote sustainable and efficient climate control. Thirdly, this research redefines the Standard Effective Temperature (SET) and comfort temperature thresholds for university buildings in Nigeria's hot and dry climate based on extensive data collection and analysis. These revised parameters are essential for ensuring the well-being and productivity of occupants while optimising energy use. Fourthly, the study showcases the potential of harnessing renewable energy sources, particularly photovoltaic (PV) technology, to power university buildings, thereby reducing their environmental impact.-Finally, the research offers insights into effective maintenance practices and retrofitting measures, which can improve the existing structures and support the sustainable evolution of educational facilities in the region.

Future research should encompass a wider variety of buildings in different climatic zones to develop comprehensive national building codes. The research focused on analyzing architectural design characteristics in the chapters. Conducting additional studies on a more diverse range of buildings could provide a deeper understanding of other architectural design factors that impact the indoor environmental quality (IEQ) of buildings beyond those examined in this study. Detailed investigations into architectural material science and thermal performance (including both traditional and composite materials), the design and comfort performance of indoor landscaping elements, costing of building maintenance/retrofitting upgrade and the thermal performance and design of interior materials are necessary to ascertain their overall influence on the IEQ of buildings in the country.

1.12 Thesis Structure

The thesis is organised into the following chapters:

Chapter 1: The chapter describes the study background, contextual framework, and focus of the study, which includes a review of the tropical hot/dry climatic conditions of Nigeria and overheating phenomena that inform the need for evaluations of the University buildings for the performance improvement of building form towards provisions of thermal comfort, IEQ, and energy efficiency. It highlighted the application of the methodology for achieving the research goal.

Chapter 2: The literature review of the recommended passive design strategies for hot/dry climates was discussed and analysed based on established minimum standard documents such as ASHRAE and CIBSE. The ASHRAE-55 occupancy and thermal comfort standard and energy efficiency for cooling buildings are also examined to determine the commonly recommended sections for achieving minimum IEQ standards in the assessment process. A conference paper entitled "Review of Strategy for Assessing the Thermal Performance of Institutional Building Form in Hot Dry Climate of Nigeria" (Bena et al., 2019) was published as part of this review.

Chapter 3: Outlined the two case study buildings, the Architectural studio and a classroom complex. The chapter explores the context of building form, orientation, construction features of buildings, building elements, functional spaces, zoning, and characteristics of the indoor learning spaces and building features that are critical to the maintenance of the facility in the climate and environment, in the assessment process and influence the delivery of passive techniques.

Chapter 4: The Chapter focused on the post-occupancy assessment of the Architectural Studio complex case study building at the Federal University Birnin Kebbi. The chapter covers both subjective and objective evaluation methodologies. The subjective process includes a questionnaire and structural interview evaluation, while the objective process involves instrumentation and monitoring of space measurement through data logging devices to measure the environmental parameters. A new SET and comfort temperature for the reference building is calculated using both monitored and global system-weather data. A conference paper entitled" (Bena et al., 2019) was published on; Analysis of Thermal Comfort in a University Building During the Hot/Dry Season in Kebbi State, Nigeria. In SET Nottingham (Ed.), 20th International Conference on Sustainable Energy Technologies as part of this review.

Chapter 5: Chapter 5 presents a post-occupancy assessment of the second case study building, a classroom complex located in the faculty layout of the University. The indoor space of the building was analysed through field surveys and measurements. To evaluate the user experience, a survey and both subjective and objective methods such as interviews, questionnaires, and environmental monitoring were conducted. The results helped to determine new SET and comfort temperature for the reference building, and these findings served as input for the parametric simulations conducted in subsequent chapters.

Chapter 6: The Architectural Studio Complex (Case study) building analysis was conducted using a computer-based dynamic simulations tool, the IESVE. This tool's methodology, process, and application were described in detail. The section focused on the parametric evaluation of the impact of passive design strategies, sun cast, solar heat gain, thermal mass, ventilation, and shading on the occupants' thermal performance, energy savings, and comfort tests and analysis. The simulations resulted in the solar heat gain factor derivation, and the coefficient was also derived to evaluate performance.

Chapter 7: The parametric (simulation) process of assessment and methodology using the IESVE tool was explored to calculate and analyse occupants' thermal comfort and energy savings of the classroom complex. The solar heat gain factor and building coefficients were derived for performance efficiency. A conference paper entitled: "Exploration of Simulation Methodology for Thermal Comfort Assessment of Educational Buildings in Nigeria." (Bena et al., 2023) was published.

Chapter 8: This Chapter presents the research conclusions and recommendations regarding the assessment of referenced buildings through passive strategies. These recommendations are intended to be incorporated into the national policy document, specifically the BEE and NNBC, as minimum building regulation standards for indoor environmental quality, thermal comfort, and energy efficiency. The report also acknowledges the limitations of the current work and suggests areas for future research.

CHAPTER TWO

2. REVIEW OF PASSIVE DESIGN STRATEGIES IN THE HOT/DRY CLIMATE OF NIGERIA

2.1 Introduction

This chapter reviews passive design strategies for the tropical hot-dry environments of Nigeria to lay the rational foundation for applying the research methodology and gaining an understanding of building performance indices. It also highlights the minimum guidelines and standards for improving comfort performances applicable to buildings in these climate zones.

2.2 Building Design Considerations

A climate-responsive approach to building design involves reviewing the local climate and establishing the nature of the problem to satisfy human requirements (CLEAR, 2023a). With increases in global temperatures, the risk of overheating is expected to rise in buildings of hot-dry climates, resulting in a higher reliance on unsustainable energy-intensive mechanical cooling systems to provide thermal comfort (CLEAR, 2023a Foruzanmehr, 2017) Overheating and hot-dry air are the main concerns when constructing buildings in hot-dry climates. This can be addressed by analysing climatic conditions using a psychrometric chart design strategy to ensure passive cooling strategies achieve comfort and attain environmental design objectives in educational buildings (Arup, 2016).

The requirement for passive design of buildings is a process that involves several construction operational strategies and target objectives that can be achieved, which include the following.

i. Consider designing with climate to provide orientation, protection, and shading.
ii. Comfortably maintaining the indoor ambient temperature that relies on building type, shape geometry, and occupancy.
iii. Minimizing heat gains and promoting heat loss,
iv. Ensure desired building orientation (existing requires retrofitting).
v. Consider protecting building form and geometry from undesirable thermal gains and promoting thermal loss.
vi. Materials and building skin components are selected to reduce heat gains by conduction, convection, and radiation (for new design).
vii. Control humidity and prevent thermal loss in buildings. (Hausladen et al., 2011).

Passive cooling refers to any technologies or design features adopted to reduce the temperature of buildings without the need for active power mechanical systems. The passive design responds to local climate and site conditions to maximise building users' thermal comfort and health while minimising energy use. The key to designing a passive building is to take advantage of the local climate (Arup, 2016, Taleb, 2014).

This passive technique in design and construction can promote the achievement of the main target of the quality of the indoor environment by utilising outdoor conditions. To achieve balanced interior conditions, the passive design incorporates solar design and relies on natural processes for heating or cooling buildings. Radiation, conduction, or convection are the thermal energy transfer processes in buildings. Reducing the rate of heat gains in the building and promoting the removal of excess heat from the building through passive design is necessary to maintain a comfortable environment within a structure in a hot climate (Ali, 2018; Kamal, 2012).

2.2.1 Climatic consideration

In hot climates, indoor spaces require cooling in summer periods, ideally through passive and efficient cooling strategies. Climate should be considered for passive design and efficient thermal comfort in all global climates, (Guevara et al., 2021, Mobolade & Pourvahidi, 2020, Lavafpour and Surat, 2011). The following are some considerations when studying thermal comfort in hot climates.

i. Solar radiation is significant while designing tropical hot/dry climates. It is a source of light and energy; solar radiation is an important planning factor; it reduces the heating energy demand and significantly influences room climate in summer. A good building plan should include enough daylight provision and good vision to control the effect of solar heating. The outdoor light levels determine the indoor daylight provision, the d glazing percentage, and the form of glazing used.

ii. Building type: Educational buildings differ in operational use and occupancy from other building types. Occupant densities and activities in the building result in internal gains that increase or reduce the cooling loads. Further, the thermal comfort criteria will determine how comfort will be restored.

iii. The construction and design of a building have a profound impact on its indoor environment and can influence minimising the need for active cooling systems. Adjusting various aspects of a building, such as taking advantage of the urban context's distance, orientation, and height, can achieve desired thermal responses. Moreover, incorporating materials with excellent insulation capabilities can significantly lower solar gains, as demonstrated by (Trepci et al., 2021; Thorpe, 2018).

2.2.2 Heat Gain in Buildings

Depending on the location, climate, and weather, heat gains or loss in buildings are desired based on the required conditions for achieving comfort. Achieving heat gain and loss lies in factors such as building orientation, managing internal gains, ventilation outlets, and other fabric elements. The phenomena of heat gain in buildings must be calculated and factored into the building's design. Heat gains in buildings arise from the conduction, convection, and radiation through the following sources: occupants' body heat; specific heating systems; cooking; clothes cleaning and drying; output from electrical/electronic devices and equipment; use of hot water; outside temperature conducted through the roof, walls, and floor; direct solar insolation through the glazing; air movement through the building. (CLEAR, 2023b, CIBSE, 2017).

Building type, occupancy patterns, and activities in the building result in internal gains. These factors affect the energy efficiency target of the building and the cooling loads. For instance, school buildings' operational use and occupancy differ from other building types. Further, the thermal comfort criteria will determine how comfort must be restored. A building can be examined regarding heat inputs and outputs rather than just metabolic heat gains and losses of the occupants. Concerning the latter, detailed aspects of the building assessment and evaluations may be required to determine the thermal performances of the building largely through user responses.

A building constructed with good materials, high thermal resistance, and good insulation properties can considerably regulate and reduce solar heat gains because heat gain and loss behave similarly to a human's natural body exchange process. Heat energy tends to disperse uniformly until a diffused homogeneous thermal field is attained. By conduction, convection, and radiation, heat tends to move from areas with higher temperatures to those with lower temperatures; this can result in the entire building fabric: walls, roof, floors, and frames (windows and doors). Calculations based on steady-state assumptions are useful to determine the maximum heat loss or gain rate and establish the cooling or heating load for passive or mechanical installations to maintain the existing thermal condition in the building. The equations and calculation methods below are valid only when the outdoor and indoor temperatures are constant. The building thermal heat balance equation is given by (Szokolay, 2008).

$$Q_i + Q_s + Q_c + Q_v + Q_e = \Delta S \qquad (2\text{-}1)$$

Where: Q_i are the total internal heat gains, Q_c is conduction heat gain or loss of the building envelope, Q_v is ventilation heat gain or loss, Q_e is evaporative heat loss and Q_s is the solar heat gain, where ΔS is the change in heat stored in the building. The effect of solar radiation on opaque surfaces can be included in the above by using the air temperature concept while solar heat gain through transparent surfaces (windows), $Q_{s.}$, is evaluated separately and is expressed as:

$$Q_s = AI\theta \qquad (2\text{-}2)$$

Where A is the surface area through which the heat flows, I is the radiation heat flow density, and θ is the solar gain factor of the window glass.

Overheating issues in buildings can be exacerbated by internal heat gains associated with equipment's heat, intense artificial lighting, and occupants' metabolic heat generation. The latter depends on the type of activities taking place in the occupied buildings. For example, occupants' metabolic heat rate in sedentary and moderate movement is about 130-160 W; when in walking and lifting/pushing activities, it increases to 290-410 W, while in sustained heavy work out such as sports centres, the metabolic rate can reach 500-799 W (CLEAR, 2023b).

2.2.3 Solar heat gain control

Passive cooling techniques in hot climates are important because they offer viable solutions for achieving minimum thermal comfort standard requirements for occupants of buildings (Taleb, 2014; NESP, 2017; Douglas, 2018; Zeinelabdein et al., 2019).

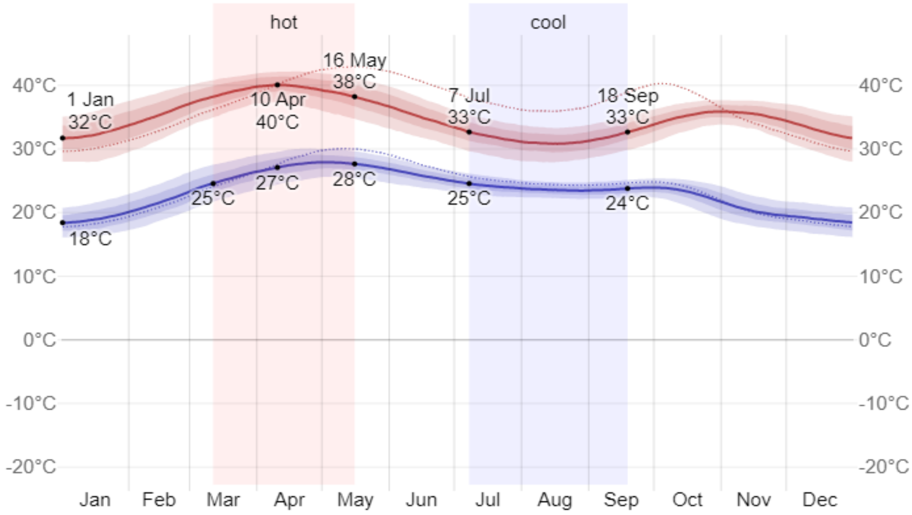


Figure 2-1 The temperature bands are shown on the daily average high (red line) and low (blue line) temperatures. The related average perceived temperatures are shown as thin dotted lines. Source; (Weathersparks, 2023b).

Table 2.1 Summary of key passive cooling strategies in hot, dry climates

S/no	Key passive Strategies	Hot and Dry Climate
1	Climatic conditions	High ambient temperature, solar radiation levels, direct/reflected sunlight, and dust storms.
2	Microclimate design approach	Compact forms, shade, and shelter for public spaces; glare control; roughness/ low reflective colours; evaporative cooling: Plant vegetation in windward location, water bodies, protected urban edges from hot winds, narrow roads/ alleys, and mixed building heights.
3.	Building design approach	Orientation: Windows facing north and south with overhangs or external shading Building form: Compact geometry reducing skin area, buffer zones and thermal zoning, daylighting, night-cooling systems, and evaporative cooling towers. Materials: A roof with a high solar roof index (SRI), e.g., cool roof, exhibits a combined high reflectivity and emissivity. High thermal mass, exterior insulation for reducing heat gains in the day. Windows with visible light transmission (VLT) > 60%; ideal for daylighting in, classrooms, and design studios for visual clarity.

In tropical climates with intense solar radiation, the basic strategy is orienting the building (design principle) and shading (design and retrofitting) for existing buildings, as contained in Table 2.1.

From the climate overview of Birnin Kebbi town, the hot season lasts from 11 March to 16 May. The average daily high temperature exceeds 38 °C and lasts 2.1 months. With an average high temperature of 40°C and a low temperature of 27°C, April is the hottest month in Birnin Kebbi. The cold season has an average daily high temperature of < 33°C and an average low temperature of 19°C, lasting 2.3 months. January is the coldest month, providing an avenue for passive adjustment to care for the climate in comfort provision (Weathersparks, 2023b).

i. Orientation

In regions near the equator, such as Nigeria's hot/dry climate zone, the sun is always\ overhead, and the horizontal surface receives the greatest intensity from solar radiation. The east and west orientations receive the second-greatest solar intensities. The north and south orientations receive the least intensity of solar radiation and for only a short duration of the year. The priority of solar strategy in passive solar design and construction is to reduce radiation inputs. Figure 2-2 illustrates the prepared, north-to-south orientation of the building as ideal; other techniques include using building elements to shade the form and arranging buildings to shade each other (Hausladen et al., 2011).

The orientation of buildings and the degree of shading from nearby structures or vegetation directly impact the amount of natural light and solar heat that penetrates indoor spaces. This consideration is crucial when evaluating how a building's positioning affects its energy consumption within a specific climate. Maximizing the utilization of natural daylight presents opportunities to reduce reliance on artificial lighting through sustainable means. Furthermore, external shading solutions, like vertical and horizontal elements, offer a means to prevent overheating from solar exposure and reduce glare.

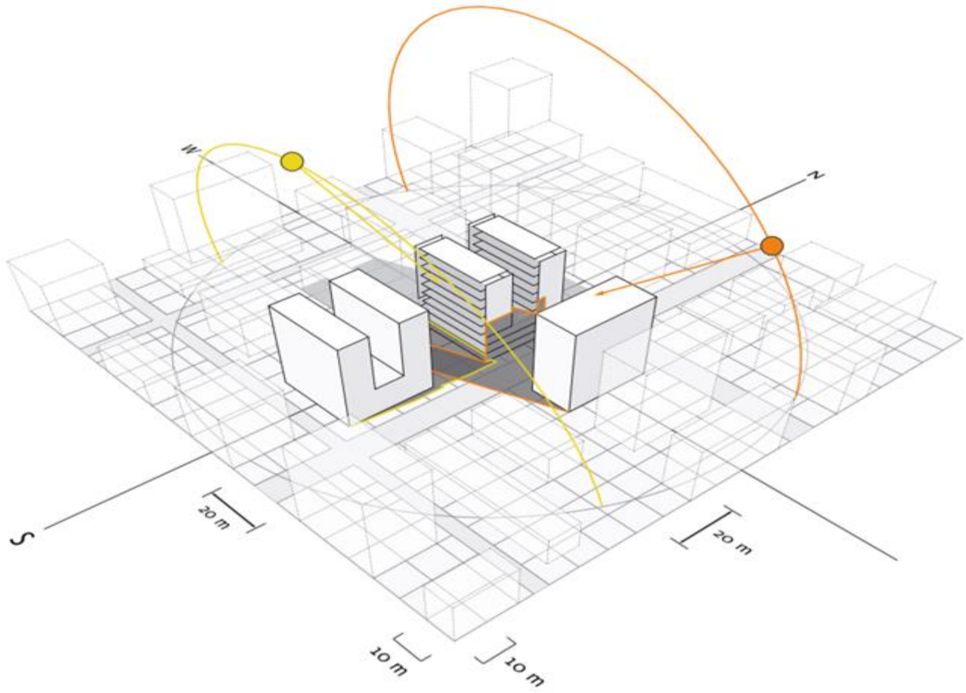


Figure 2-2 Building orientation priority for reducing solar radiation impacts. Source: (Hausladen et al., 2011).

The strategic needs for cooling and humidifying buildings in the climate are:

- **i.** No passive solar gain is required in winter.
- **ii.** Solar energy generation affects the east, south, and west elevations of buildings and, hence, needs protection.
- **iii.** Thermal protection to be added to the facade to prevent transmission and heat gains.
- **iv.** The outer wall should absorb only a small degree of radiation.
- **v.** The glazing percentage is dictated by solar input. It should be as low as possible on all sides, around 30% to 40%, with reduced glazing percentage, external sun protection, and intensive night ventilation.
- **vi.** Sun protection to the east and west facades from direct and diffuse radiation.
- **vii.** The glazing's g-value should be lower than 0.4. Illustrated in Figure 2-3. (Carbon Trust, 2018; Lawrence & Keime, 2016).

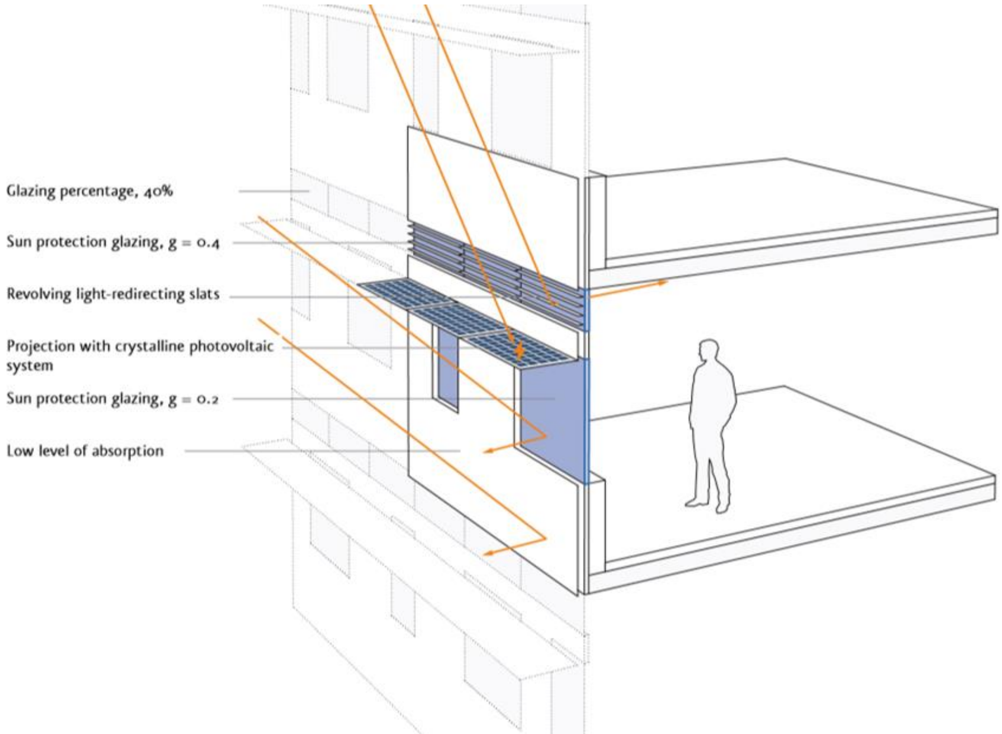


Figure 2-3 Facade concept Strategies of optimising energy and daylight for the tropical climate, Source; (Hausladen et al., 2011).

ii. Solar Shading

The best way to prevent overheating and unwanted glare from direct sunlight is to shade the building, preventing sunlight from reaching it, or to prevent solar gain in the interior of the building during the periods when it is in danger of overheating. Once hot air is inside the building, or if unwanted temperatures are generated, passive cooling techniques should be used to change the situation (Tang & Chin, 2013).

The passive solar shading technique is a significant design and building strategy that is systematic for maintaining and retrofitting building fabric elements. Active devices and methods are used to improve indoor comfort and building energy performance. Thorpe, (2018). However, the cooling is provided by radiant exchange, radiant shielding, air movement, and control (which allows personal cooling by evaporation). The application of optional techniques of massive walls and floors, large, openable windows, slatted shutters, overhangs, and hoods are integral fabric devices (Thorpe, 2018). Inter-building shading on energy performance, with an emphasis on the cooling demand patterns for buildings of different types and sizes, is one of the passive strategies employed by professionals while designing urban canters with the combined effects of urban context height, distance, and orientation can lead to significant reductions in cooling demand, reaching up to 26% for total cooling loads and 24% for peak cooling loads, explained in Trepci et al., (2021) research in urban cities of hot climates to leverage orientation and internal building shading effects for energy conservation.

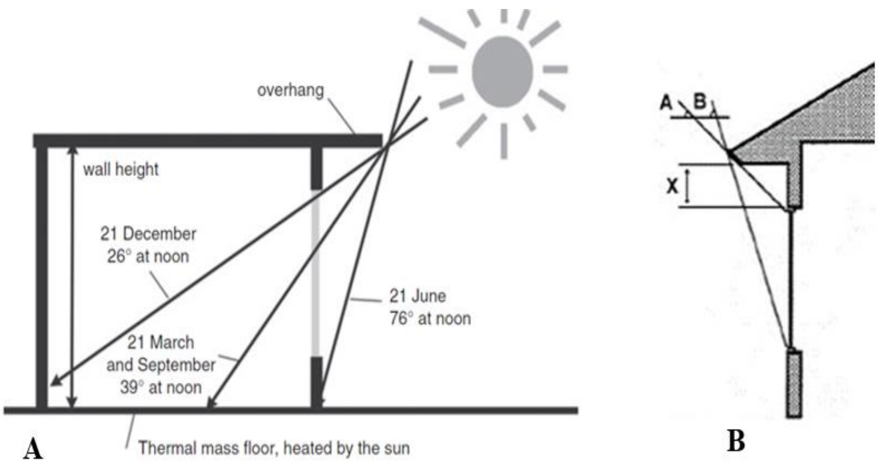


Figure 2-4 Section (A) Solar radiation protection into the building, (B) Angles protection of windows from sunlight using roof overhang. Source, (Thorpe, 2018).

Shading is a principal tactic to protect the building from direct sunlight, illustrated in Figure 2-4. The guiding principles include.

i. Covering roofs and courtyards with deciduous vegetation to provide shade and reduce the temperature of the roof surface.
ii. Controlling winter solar access.
iii. Provision of horizontal overhangs or vertical fins to prevent overheating while preserving natural daylighting.

iv. Plant trees and shrubs along the east and west walls to protect summer windows through vertical shading.

v. Horizontal shading for south-facing windows.

vi. Highly textured walls absorb less heat, and when a portion of the protruding areas, the wall surface has a deep shadow cast.

vii. Green roofs, earthenware pots filled, and reflective surfaces painted with oxide white paint/whitewash are all techniques practiced widely to prevent heat from penetrating the roof.

viii. Shading devices construction temporary or permanent outside along openings. (Thorpe, 2018).

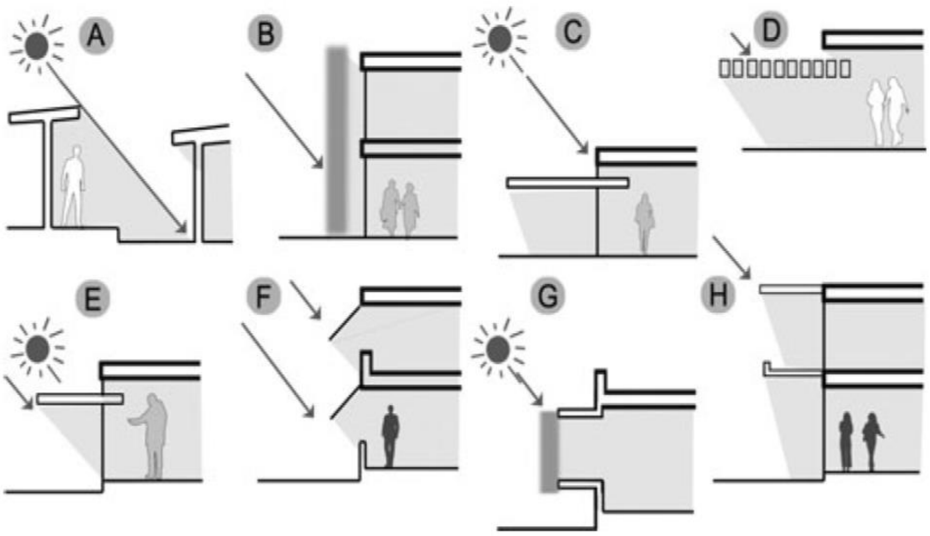


Figure 2-5 Different shading devices: (A) shading sun orientation, (B) by barrier, (C); by horizontal cantilever overhang, (D) Eggcrate horizontal grills, (E) horizontal cantilever to protect glazing, (F) Angular varier shading, (G); Vertical grill on projected opening, (H); Roof cantilever at levels. Source, (Thorpe, 2018).

Vertical and horizontal shading devices are characterised by vertical and horizontal shadow angles (VSA). External egg crate devices consist of a combination of both the VSA and HSA. Blades of shallow depth with close spacing can give an HSA like that given by blades of deeper depth and wider spacing.

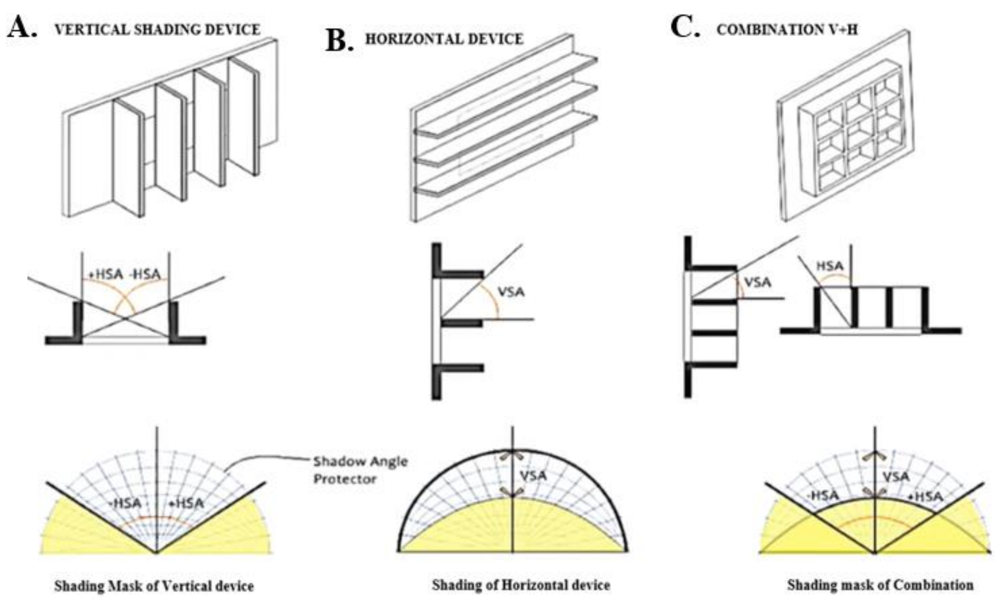


Figure 2-6 Different shading types: vertical, horizontal, and combination.

Given the wide variety of buildings and the range of climates in which they can be found, it is difficult to generalise the design and adoption of shading devices. However, the following design recommendations can be used as general guidelines:

- **i.** Fixing overhangs on the south-facing glass to control direct beam solar radiation. Other measures, such as Low-E glazing, should control indirect (diffuse) radiation.
- **ii.** Limiting the amount of east and west glass since it is harder to shade than south glass. Consider using landscaping to shade east and west exposures.
- **iii.** Consider not shading the north-facing glass at continental United States latitudes since it receives little direct solar gain. In the tropics, disregard this rule of thumb since the north side of a building will receive more direct solar gain. Also, in the tropics, consider shading the roof even if there are no skylights since the roof is a major source of transmitted solar gain into the building.
- **iv.** Remember that shading affects daylighting; consider both simultaneously. For example, a light shelf bounces natural light deep into a room through high windows while shading lower windows.

v. Interior shading devices such as venetian blinds or vertical louvers do not reduce cooling loads since the solar gain in hot-dry climates always radiates into the indoor space. However, these interior devices offer glare control and can contribute to visual insight and comfort in the workplace.

vi. Study sun angles. Understanding sun angles is critical to various design aspects, including determining basic building orientation, selecting shading devices, and placing Building Integrated Photovoltaic (BIPV) panels or solar collectors.

vii. Carefully consider the durability of shading devices. Over time, operable shading devices requires considerable maintenance and repair.

viii. When relying on landscape elements for shading, consider the cost of landscape maintenance and upkeep on life-cycle costs.

ix. Shading strategies that work well at one latitude may be inappropriate for other sites at different latitudes and the application of shading devices varies from one building to another according to (Prowler, 2016).

iii. Building Form and Shape

Building envelope refers to the roof, walls, windows, doors, floors, and foundations. The envelope is the building structure exposed to the environment in which design and construction affect internal temperature and heat loss. The smaller the building's external area, the less surface area is available for heat transfer from/to the indoor space. While building geometry refers to measurements relating to building configuration and arrangements, in a broader sense, it relates to building components; its envelope interacts with the interior and mediates the difference between outdoor and desired indoor conditions. Equally, forms play the leading role in achieving the energy efficiency of a structure and must be considered in design planning and construction. Good design of form can minimize and downsize heating and cooling requirements or eliminate the need for them all (Gerhard et al., 2012; Hanan, 2014; Zero Carbon Hub, 2016).

Figure 2-7 From the Rashdi and Embi, (2016) research by analysis explored how different building forms and the addition of windows affect cooling loads. It investigated the response of eight distinct building shapes to hot, humid climates and their influence on reducing cooling requirements. The findings revealed that adding windows to the rectangular (I-shaped) form increased the cooling load by 62%. Conversely, L, O, courtyard, and U shapes had lower cooling needs than the modified I form. The increased cooling load in the I form is due to its loose structure, which exposes more surface area to solar heat gains. In contrast, compact forms typically have lower cooling needs, regardless of whether they include a courtyard. A lower surface-to-volume ratio indicates a more compact form and a reduced cooling load. Although different orientations can moderate cooling, positioning the long axis of buildings where window and openings pointing to the north direction is optimal in achieving a lower cooling load.

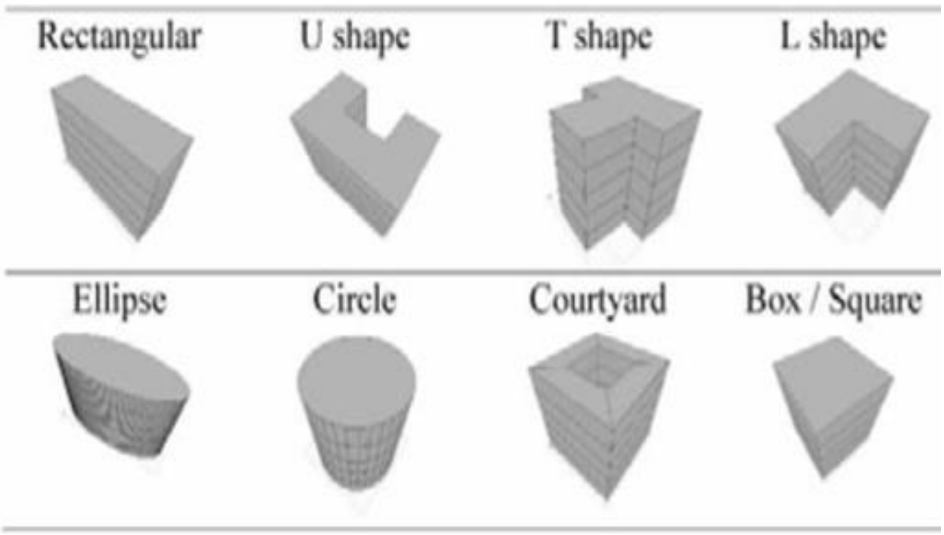


Figure 2-7 Different 3D configurations of form shape according to Architectural concepts Source: (Rashdi & Embi, 2016).

Figure 2-8 From the research, Adinugroho and Gadi (2018) evaluate the design process to optimise energy efficiency. Eight prismatic forms derived from isometric crystals were simulated. They were tested in hot and cold climates in three cities to establish a self-shading ratio form indicator. Except for CUB-8, results indicate that prismatic models consistently predict lower annual cooling and heating loads than neutral (N-CUB) across all tested locations. The average solar irradiance on the building surface of the prismatic models is generally lower than the N-CUB value, except for CUB-8. Different prismatic shapes, with the same shape factor derived from a cube, impact solar irradiance and subsequently influence heating and cooling loads. For shading impact, a higher slope angle reduces the effect of solar radiation, while the surface area has an offsetting effect. For example, CUB-3 and CUB-7 both exhibit self-shading and have the highest solar irradiance among the other models, but their self-shading and cooling load properties contradict each other.

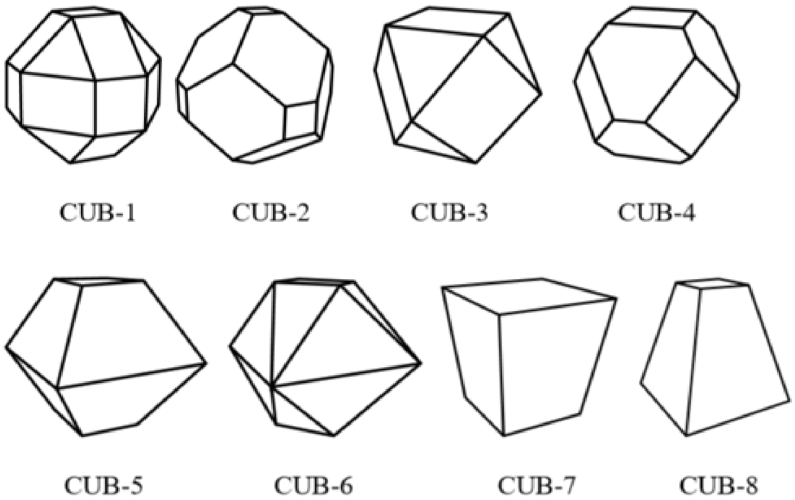


Figure 2-8 Eight prismatic forms simulated for energy efficiency. Source: (Adinugroho & Gadi, 2018).

The building shape factor is the ratio of building length to building depth. In numerous studies with orientation, these factors define the percentage of the facade exposed at each cardinal point. Both factors are generally studied together (Alshenafi and Sharples, 2018; Shakila *et al.* 2018; Adinugroho and Gadi, 2018; Chia *et al.* 2013). Combining shape and orientation optimization can result in passive cooling benefits. The composition of form in relation to the wind-to-wall ratio can help achieve thermal comfort levels of 20-50% by utilizing proper orientation and shape. However, manipulating form shape via design options offers a potential energy-saving mechanism that can vary in different climates. In hot climates, complex building shapes expose their fabric elements to solar radiation (Rashdi & Embi, 2016). Prismatic form shapes in Figure 2-8 can save energy because the shape casts shade and shadows the lower floor height, cooling the interior and reducing energy consumption (Adinugroho and Gadi, 2018). Research conducted by Rodrigues et al. (2016) demonstrated how the improvement of building materials and techniques in modern construction through the addition of thermal mass Phase Change Material on a fabricated timber modular building construction regulates indoor temperature and provides comfort. This highlights the importance of making buildings tight to mitigate overheating in homes compared to the PassivHaus guide.

Heating building interiors in various climates can result in high operational costs due to active energy consumption and usage. Other sources of heat buildup include installed components, such as electrical gadgets or mechanical systems, as well as the actions of occupants. Proper maintenance can reduce a building's energy consumption, as stated by (The Carbon Trust, 2018). Energy-saving strategies for building and increasing supply in operation are many and come in different dimensions apart from changes to its mechanical and electrical operations, consumption, and usage; building form elements such as (roof, walls, floors, and windows/openings) may also provide savings using passive techniques by controlling the flow of heat through building fabric surfaces (Raynsford, 2016).

iv. Building fabric heat transfer

- **Conduction:** In buildings, heat is transmitted by conduction, convection, and radiation. Due to a temperature difference across a body and a medium of heat transfer, conduction is crucial in buildings with the exchange in outdoor temperature and the difference between the inside and the outside indices. Internal heat diffuses into external space through conduction due to temperature differences across a body. Conduction is one of the primary possible heat transfer routes via which internal warmth or cooling might escape to the outside. It can lead to high operating costs, significant carbon emissions, and uncomfortable occupants (The Carbon Trust, 2018).

The U-value is the reciprocal sum of a body's thermal resistances plus its inside and outside surface resistances. Conductivity is more accurately expressed by a material's R-value, which is the inverse of its thermal resistance and does not include a surface component. The thermal mass of building components can also achieve an insulating effect. Thermal mass describes the ability of a material to absorb, store, and release heat energy. It is the variations in internal and external heat absorption and retention conditions as the temperatures rise and reduce. The main forms of heat transfer through the building envelope include:

Wall- Conduction of heat may occur through the walls either inwards or outwards, the rate of which is denoted by Qc (convective and radiant components in the transfer of the same heat at the surfaces are included in the term transmittance).

$$Q_c = UA\Delta T \qquad (2\text{-}3)$$

where:

Q = the resultant heat flow (Watts)

A = the surface area through which the heat flows (m²)

ΔT = the temperature difference between the warm and cold sides of the material (K), and

U = the overall U-value (transmittance) of the wall (W/m^2 K)

Similarly, the overall thermal resistance, R_t, of the building element is a measure of heat resistance through a given thickness and is expressed as:

$$R_t = R_{si} + \frac{d_i}{\lambda_i} + R_{so} \qquad (2.4)$$

$$U = \frac{1}{R_t} \tag{2.5}$$

Where R_t = the total overall resistance of the element, R_{so} & R_{si} are the outside and inside surface resistances, respectively, di and λ_i are the thickness and thermal conductivity of the material *i*.

- **Convection:** Convection and advection cause a fluid, like air, to flow. Air movement is crucial in building construction because it helps moderate interior temperatures. However, air movement inside buildings can be difficult to predict without using tracer gas or computational fluid dynamics (CFD) modelling tools.

- **Radiation:** Thermal radiation is produced by all bodies at a temperature above zero degrees Kelvin. Heat gain in buildings can be directly from the sun through transparent surfaces (short-wave) or absorbed first by buildings' opaque walls and then radiated as long-wave radiation.

- **Heat Lost by Roof:** Over 20% of heat in a building is lost through the roof. Installing much insulation in an uninsulated pitched roof is a cost-effective way to improve the efficiency of the building fabric and save money, reducing heat loss through the roof by over 80%. Upgrading existing insulation offers significant results, providing no dampness. Ceilings in multi-story buildings, it is beneficial to insulate between the ceiling and floor spaces; it eases the difficulty of heating lower floors and reduces the problem of overheating on higher floors (The Carbon Trust, 2018).

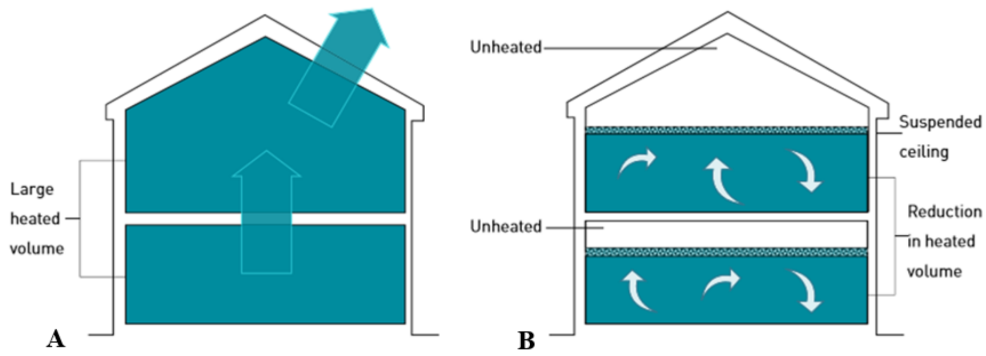


Figure 2-9 (A) Heat loss through uninsulated stories and (B) Improved heat retention due to inter-floor insulation.

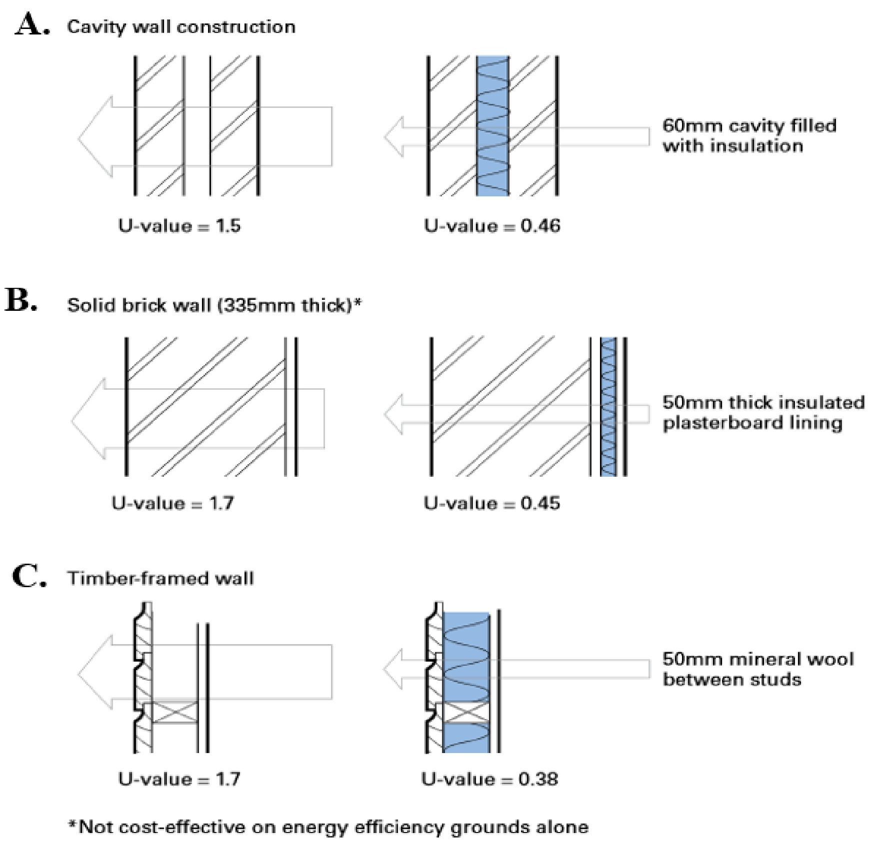


Figure 2-10 Insulation in different wall types (A, B, and C) Source: (The Carbon Trust, 2018).

- **Walls:** Around 9% of heat loss in a building is through the fabric of the walls. External wall insulation is the most common, and effective, method of insulating solid external walls by applying insulation boards to the outer surfaces of the building and protecting it with a specialist render or cladding system. It can be done in a new build construction and during the refurbishment of existing buildings. This method brings several benefits:

- **Windows:** Windows can reduce lighting, heating, and mechanical cooling requirements. However, they can also account for over one-fourth of a building's heat loss. Glazing increases solar heat, increasing overheating indoors of buildings in hot/dry climates. Too much glazing can also make buildings uncomfortably warm in the summertime in colder climates.

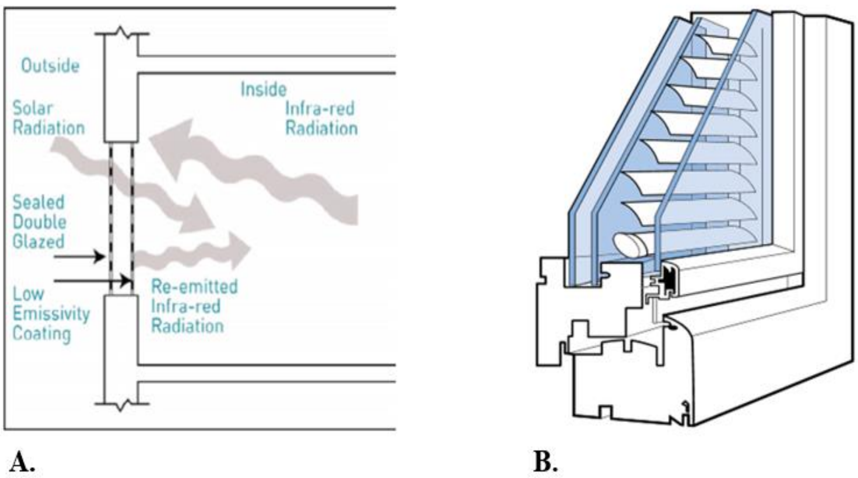


Figure 2-11 (A) Solar gain and the role of glazing B) Triple glazing to manufacturers' specs. Source: (The Carbon Trust, 2018).

The main factors affecting a window's performance are:

i. Several panes of glass that make up a glazing unit (single, double, or triple).
ii. Specification of the glass used.
iii. The type of gas used to fill the cavity between glass panes.
iv. Frame design (thermal break width).
v. Glazing unit design (insulating spacers). Remedy is achieved by keeping windows closed to reduce the loss of heated or cooled air, make good use of natural daylight occupants should, therefore, be encouraged to keep

lights switched off when there is sufficient daylight; Redirect the sun coming into buildings through glazing and by lowering blinds.

- **Doors:** Doors are essential building elements that provide easy access and exits. However, opening doors can allow uncontrolled air into a building, reducing comfort and wasting energy (Figure 2-12 illustrates). Through user modes of handling and operations, behavioural change will regulate the heat exchange.

- **Floors:** Floors are often overlooked as an area for energy savings, but nearly 10% of heat loss from a building will occur via the ground floor (Carbon Trust: Building fabric, 2018). Figure 2.12 illustrates various percentages of heat loss to the environment by building at floor level and other fabric elements.

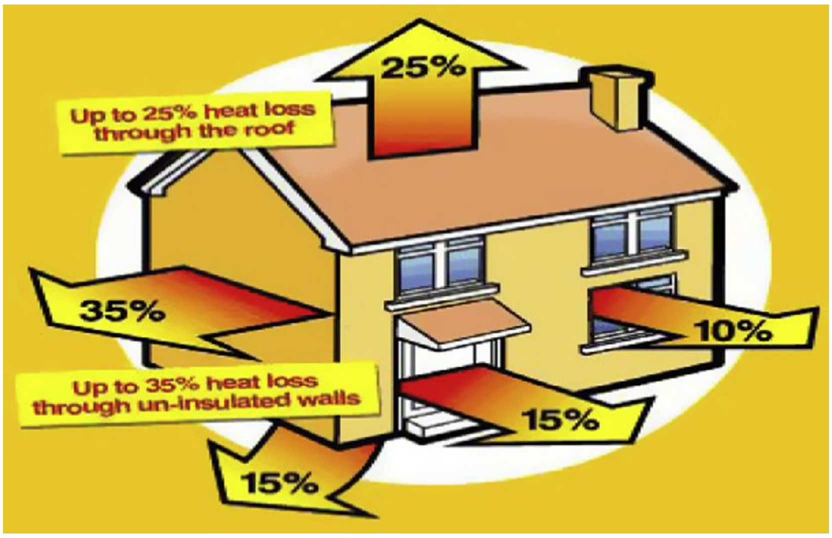


Figure 2-12 Energy is emitted by different parts of the building. Source: <http://www.haringey.gov.uk/energyadvice.htm>.

- **Form:** A building's shape and proportion exposed to the environment will also affect internal temperatures and heat loss. The smaller the external surface area of a building, the less opportunity there is for heat to escape; however, this can also reduce natural lighting and ventilation. The design of a building has a significant impact on its energy consumption. This is determined by the surface area to volume (S/V) ratio and heat loss form factor (FF). The S/V ratio measures the compactness of a building and is calculated as.

$$\text{Compactness } (C) = \frac{\text{Volume}}{\text{Surface Area}} \tag{2-6}$$

A smaller building with the same shape as a larger one will have a higher S/V ratio, resulting in higher energy consumption for heating. The FF measures the efficiency of a building's shape, calculated as the external area of the building (excluding the ground) divided by the floor area.

$$\text{Form Factor } (FF) = \frac{\text{Heat Loss Area}}{\text{Treated Floor Area}} \tag{2-7}$$

The Passivhaus standard aims for an FF of 3 or less, as higher values make efficient heating more challenging. The FF is more relevant than the S/V ratio and favours buildings with less height and floor-to-floor space (Thorpe, 2018).

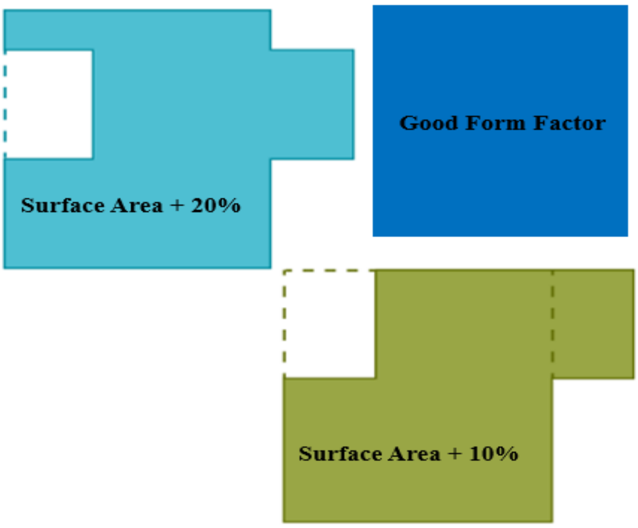


Figure 2-13 Variation in building forms shows factors of energy loss and gain. Source (Thorpe, 2018).

- **Building airtightness:** Air enters and leaves a building through controlled ventilation, windows, and air vents, and uncontrolled air infiltration, gaps, and cracks in the walls around window and door openings. Air infiltration does not ventilate a building in an energy-efficient way. Buildings that leak air also leak money, as additional energy is needed to heat or cool the outside air entering the building. Improving airtightness in buildings reduces hot or cold air loss (according to the climate), thereby reducing additional heating or cooling costs. It also improves comfort and protects the building fabric by eliminating unwanted draught achieved through building sealing of building to reduce infiltration called uncontrolled ventilation.

- **Condensation:** Condensation can occur on the surface or within the building fabric. Surface condensation occurs when warm moisture-laden air contacts a cold surface below the dewpoint. Mitigation strategies include ensuring upgraded insulation is continuous by minimizing thermal bridging. Reduced risk of condensation, reduced opportunities for thermal bridging, improved airtightness, retention of thermal mass on the inside of the building, and improved aesthetic appearance. Factors that affect the energy loss and gain in terms of heat by a building are ventilation and fabric heat loss, which are two reasons for heat loss in buildings.

2.2.4 Natural Ventilation and Infiltration Heat Gains Control

Ventilation brings fresh air and removes stale air from an occupied space. The removal of interior contaminants, the provision of oxygen for breathing, and the improvement of thermal comfort all depend on this two-way airflow. Natural ventilation is the movement of air into and out of a structure using natural forces rather than mechanical devices. It originates from the differential in air pressure between the building's interior and exterior, and it is influenced by the height of the structure and variations in interior and exterior air temperature. (Bhatia, 2020). Two types of natural ventilation can be classified as:

i. Controlled natural ventilation is the deliberate movement of air via predetermined openings like windows, doors, and ventilations while utilising natural forces (often pressures from the wind and/or temperature differential between the inside and outside of the building). The occupier typically has some degree of influence over it.

ii. Infiltration air is a major source of ventilation in structures where the envelope dominates, unlike regulated natural ventilation. It can be managed through alternative ventilation systems. Infiltration is the uncontrolled random flow of air via unintended openings caused by wind, pressures caused by temperature differences, and/or pressures caused by appliances over the building envelope. Taylor et al. (2019) gave a calculation formula for wind-driven, stack-driven, and Total Infiltration Air flow in buildings as a guide.

The design of natural ventilation systems depends on building type and local climate, and the ventilation required depends on the design of interior zones and the size and positioning of openings. The total airflow due to natural ventilation results from the combined pressure effects of wind and buoyancy caused by temperature and humidity. Common constraints to ventilation provision are based on this.

i. Poor control over the ventilation rate could lead to poor indoor air quality and high heat loss.

ii. Airflow rates and patterns may not be constant.

iii. Quality air distribution in large, deep-plan, and multi-roomed buildings may be difficult.

iv. High heat gains may result in using mechanical cooling instead of natural ventilation.

v. Ventilation provision may be unsuitable for noisy and polluted locations. Heat recovery from the exhaust air is generally not suitable for hot climates.

vi. The occupant's task is important; adjusting openings to suit ventilation provision and demand in indoor building spaces could regulate airflow (Thorpe, 2018).

Accordingly, ventilation in a building works as a ratio of the floor to ceiling height; the greater the heat gains, the more ventilation is required; however, gains should be made by other means. Overflow of air for ventilation will increase heat loss and eradicate the need to make the envelope airtight and fit slot ventilators. Openings can be under intelligent control, with the control parameters being temperature and CO_2 concentration. Heat flow into the building in and out because solar radiation occurs through walls, windows, doors, roofs, ceilings, floors, and openings/gaps by transmission, ventilation, and infiltration (Szokolay, 2008).

In most buildings, ventilation serves three functions: providing fresh air, dissipating internal heat build-up when the outside temperature (To) is lower than the inside temperature (Ti), and physiological cooling (Szokolay, 2008). In the first two instances, the Equation illustrates how the ventilation rate depends on the ventilation rate (V), often expressed in m^3/s. The heat exchange may occur in either direction with the movement of air. The heat transfer rate is expressed as.

$$Q_v = \frac{1}{3} nV\Delta T \tag{2.8}$$

Where:

V= ventilation rate (m^3/s)

ΔT = the temperature difference between outdoor and indoor air (°C)

n= number of air changes per hour

2.3 Cooling Provision of Building Indoors

Cooling is primarily used to combat heat gain and establish a thermal equilibrium promoting thermal comfort. Natural ventilation is the primary passive cooling strategy in warm areas because it can generate volumetric flow for transferring heat caused by the outdoor wind speed or stack effect and the renewal of indoor air quality. The primary goals of cooling are to reduce heat gain and establish a thermal equilibrium that would promote thermal comfort. Natural ventilation is the primary passive cooling strategy in warm areas, since it can generate volumetric flow for transferring heat caused by the outdoor wind speed or stack effect and the renewal of indoor air quality. The movement of air can be used in two ways to provide cooling. First, by ventilating a space when the outdoor temperature (To) is cooler than the indoor temperature (Ti), warm air can be expelled leaving the building cooler (CIBSE, 2015). Figure 2-14 shows how outside air flow affects the building. By providing cross ventilation that relies either on wind or stack effect, air movement can be encouraged for ventilation and physiological cooling.

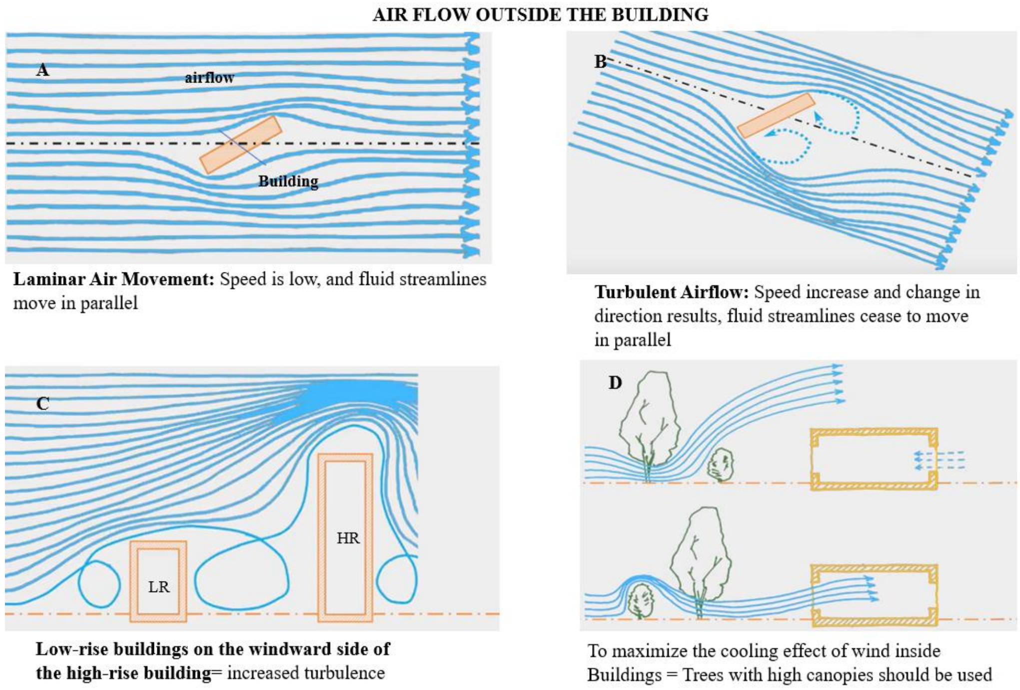


Figure 2-14 Airflow outside the building.

There should be an opening for both an inlet and an outflow for positive and negative pressure differences to be created, which will propel air movement throughout the chosen location. A natural wind flow pattern affects the outside and inside of the building; the pressure outside impacts the inside air provision and the movement.

Figures 2-15 (A, B, C, and D) show different airflow patterns relative to the positions of openings summarised, and Figure 2.17 (A and B) shows airflow relative to the presence of window overhang.

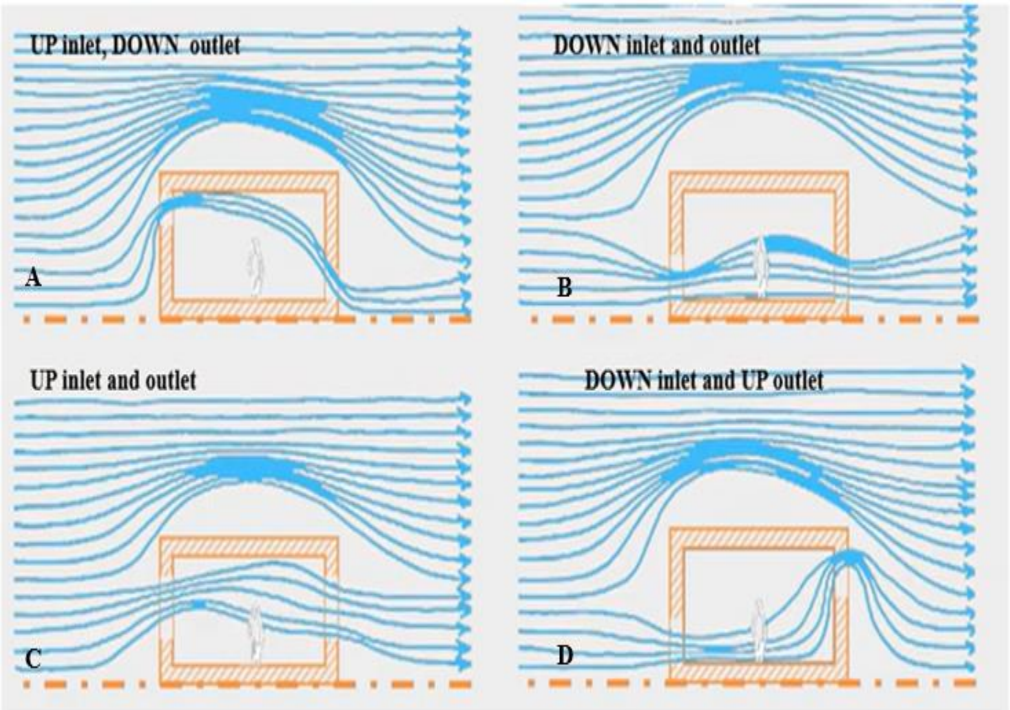
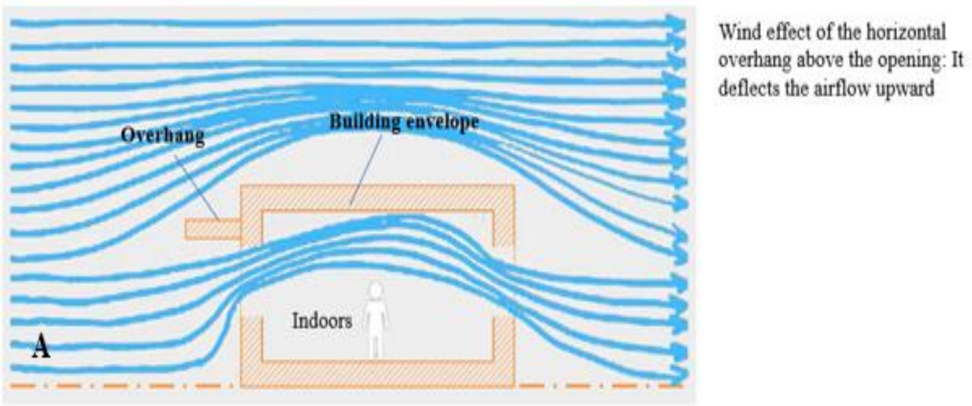


Figure 2-15 Air flow Pattern relative to position of openings (A, B, C, and D).



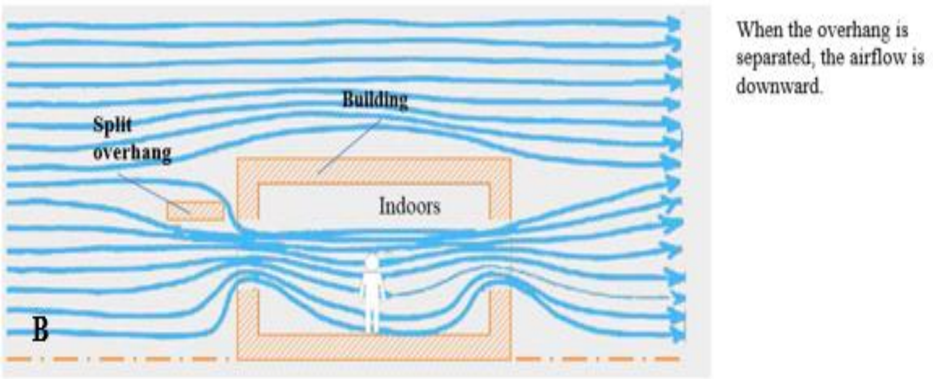


Figure 2-16 (A and B), Airflow pattern and effect of horizontal overhang through the position of openings.

Theoretically, an expression for the volume of airflow induced by wind is:

$$Q_{wind} = KAV \qquad (2.9)$$

Where:

• Q wind = volume of airflow, m^3/s [CFM]

• A = area of smaller opening, m^2 [ft^2]

• V = outdoor wind speed, m/s [fpm]

• K = coefficient of effectiveness (assumed to be 0.5 to 0.6 for perpendicular winds and 0.25 to 0.36 for diagonal winds). The coefficient of efficacy (or suction) of a door or window depends on the direction and size disparity between the entrance and exit apertures. It varies from roughly 0.3 when wind is incident at a 45° angle to 0.6 when it is incident directly at a 90° angle.

Figure 2-17 demonstrates the wind flow based on the window inlet and outlet positions. It shows that wind buoyancy plays a significant role in indoor spaces in cases A, B, and C. When the openings are aligned, as in Case A, cross ventilation is effective.

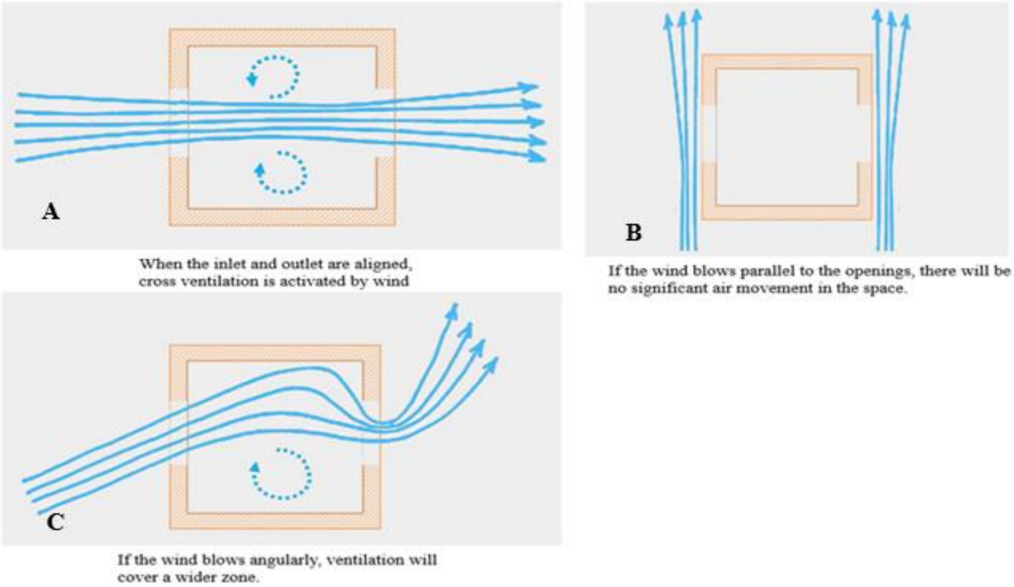


Figure 2-17(A, B, and C) Shows the effects of alignment of openings for cross ventilation.

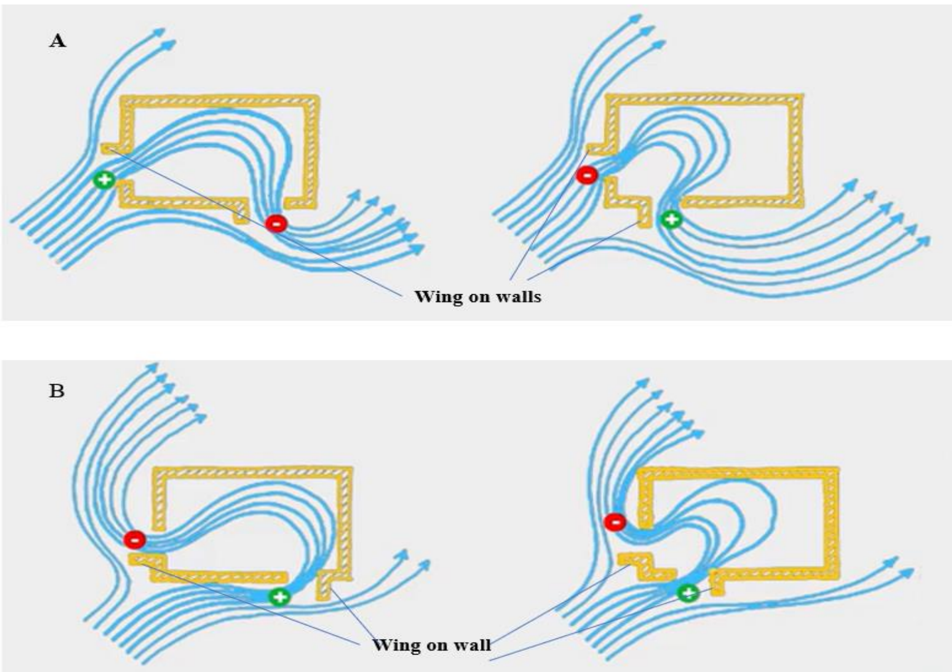


Figure 2-18 (A and B) Showing the effectiveness of wings on walls in increasing natural ventilation.

However, as illustrated in B, air movement will cease when the wind flows parallel to the openings. In Case C, angular wind flow is optimal for providing sufficient air into the room. In Figure 2.18 (A and B), wing introduction on walls is shown to be effective in increasing the flow of air into interior spaces.

2.3.1 Stack effect

The stack effect, also known as the chimney effect, occurs when there is a difference in temperature between the inside and outside of a building, considering the movement of a large volume of air. According to Hamdani et al., (2017), this effect changes air density and pressure, causing warm indoor air to rise above cold outdoor air. To facilitate natural ventilation wind flows into the internal building space through windows and vent openings, which helps drive natural ventilation air infiltration and induces air movement through the stack effect. There should be at least two ventilation openings in the building, one at the top and one at the bottom, to achieve this effect: people, lighting, and equipment inside the building cause the indoor air temperature to rise. If an opening is near the ceiling, cooler outside air can enter the lower opening while warmer air from the upper-level escapes.

Scientifically, an occupied building experiencing overheating, stack effect can act the same as a huge chimney with the same phenomenon that causes hot combustion gases due to rising temperatures. Stack ventilation uses temperature differences to move air. Since hot air is of lower pressure, it rises, making this method buoyancy ventilation. This method is more effective in high-rise buildings. Other methods for ensuring ventilation and cooling, such as Windcatchers and fans (mechanical ventilation), are more suitable for low-rise buildings. The stack effect causes hot air to rise, and its low pressure draws in fresh air from the outside, as in Figure 2-19.

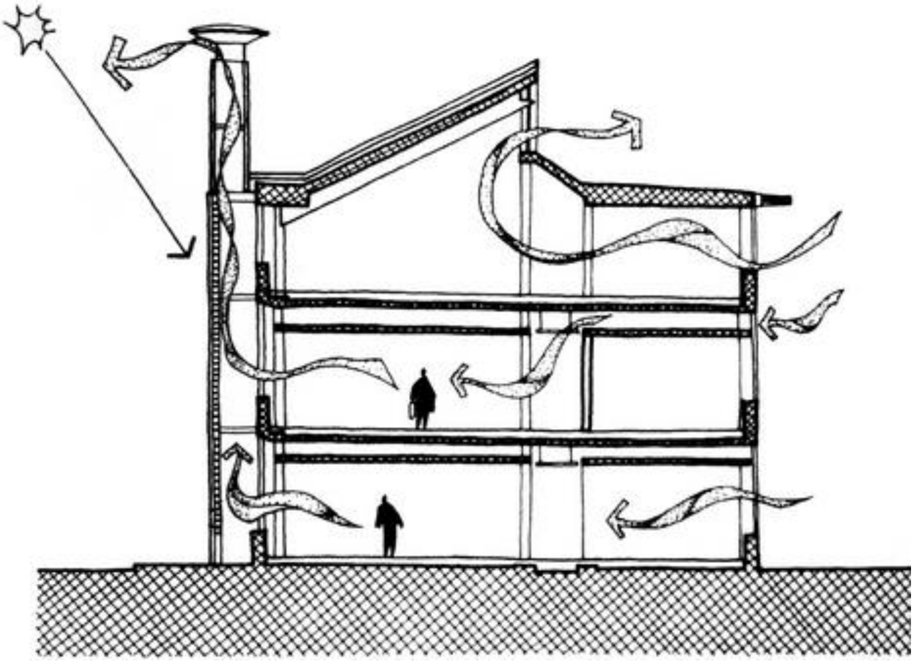


Figure 2-19 Stack effect in low rise building. Source: Brown and Mark, (2013) https://sustainabilityworkshop.venturewell.org/node/1029.html.

The stack effect is a technique for improving ventilation and passive cooling in buildings. Construction elements include stairways, halls, turrets, vents, and windcatchers. Figure 2-19b shows the features of windcatchers in modern construction (Chohan and Awad, 2022; Nejat et al., 2018; Taleb, 2014).

Figure 2-20b Modern wind catcher in Qatar University Doha, Qatar. Source; https://www.archnet.org/sites/288

- ***Windcatcher***

Windcatchers are traditional architectural elements for natural ventilation in the Middle East, particularly in humid, hot, and arid climates. The structure holds significant symbolic importance in the region's construction and design of different building types (Heidari et al., 2024). The passive system effectively aids indoor air ventilation but has limited cooling capacity (Jomehzadeh et al., 2017; Hosseini et al., 2016; Montazeri et al., 2010). Research suggests that incorporating active and passive cooling components, like fans, into the wind catcher system can enhance their effectiveness. (Hughes et al., 2012). Alternative cooling techniques, such as windows and roof shading, may also be necessary to maintain the building's symbolic character through passive retrofitting and maintenance.

- ***Climatic response***

A windcatcher's climatic response demonstrates how air movement is influenced by the stack effect resulting from thermal variations, which is used for ventilation purposes. Buildings exposed to higher temperatures in summer will contain hot air. As warm air ascends inside a building, it generates a pressure disparity, with lower pressure below and higher pressure above. In winter, the lower pressure facilitates the hot air from outside into the lower levels of the building. The temperature of the hot air then rises, continuing the cycle. Conversely, in summer or warmer climates, the stack effect is reversed. The hot outdoor air flows to the upper part of the cooler section of the building, creating a downward draft. Each building possesses a neutral pressure level (NPL), where the pressure difference between the building and its surroundings is equal. Air movement into or out of the building is minimized along this plane and increases further from it. Systems that actively facilitate the movement of air in or out of the building, such as exhaust systems, will alter the location of the NPL. Understanding the NPL of a building enables designers and building managers to concentrate on control measures where they are most essential (Park et al., 2023).

Technical guides in implementing ventilation and cooling in buildings are:

i. The construction and design increase air velocity and reduce air temperature at the building inlet through the stack ventilation process.
ii. The indoor space cooling process increases when traditional windcatchers are combined with an evaporative cooling system.
iii. Increasing the windcatcher's height also increased the airflow and relative humidity through the openings and vents to the indoor spaces; the air temperature for (cooling) declined due to the stack effects.
iv. Buildings with maximum indoor space width require more windcatchers with wider widths to avoid poor natural ventilation due to the width factor.
v. Interior mechanical facilities integrated to enhance the stack ventilation effect of windcatchers should be positioned above the window to expel stale air, as height supports this.

2.3.1 Thermal Mass

In many buildings, typical finishes such as false floors, false ceilings, and lightweight wall coverings may also have insulating air spaces that tend to render them more lightweight. These lightweight buildings respond quickly to outdoor temperature fluctuations and are more likely to result in overheating in office buildings (Rodrigues et al., 2016). It is suggested that the introduction of thermal mass can potentially avoid this. Although from the above strategy, building in this climate has 9.7% and 13.9% high thermal mass to adjust and ensure comfort provision. A building's thermal mass can decrease heat transfer into the interior in hot and dry climates. Materials with a high heat storage capacity, like concrete, warm up and cool down slowly in environments with a considerable daily range in temperature values. Designers can stabilize temperatures throughout their diurnal cycle by adding thermal mass into the building fabric; this is accomplished in three ways: by providing surfaces that act as heat sources and sinks, delaying the time it takes for indoor and outdoor temperatures to equalize, and lowering the temperature along an exterior wall. (Rodrigues et al., 2016; Szokolay, 2008).

2.3.2 Night Ventilation

In climates with a wide diurnal temperature range (an absolute minimum of 5°C), where external air temperatures are too high to provide adequate natural cooling during the day but where night-time temperatures are low enough to "pre-cool" the building in preparation for the following day, night ventilation for cooling is particularly effective (Buildings in hot climates 2008). Due to the wide variety of daily temperatures in the climate zone, this method is frequently considered for hot climates.

2.3.3 Ground cooling

The earth can frequently be used as a heat sink to offer cooling when techniques for preventing unwanted heat gains have been used, but the interior temperature of the room is still high. Temperatures below the surface are more consistent and much lower throughout the year than in the air. The surface (Chun et al., 2018, Honnekeri et al., 2014; Szokolay, 2008). It may be possible to increase cooling by increasing the building's ground contact. Direct contact with the earth or installing ground cooling pipes that transfer ground-level coolness to air diffused across the area can accomplish this. In hot and dry conditions, earth cooling is widely acknowledged to be quite effective (Alshehri et al., 2019).

2.3.4 Evaporative cooling and dehumidification

Evaporative cooling is a passive method that relies mostly on mechanical tools for better control, or less so, solely passive tools. Direct and indirect evaporative cooling are the two different available forms. When using direct evaporative cooling, warm outdoor air is passed via a surface or water-filled conduit before being replaced with cooler inside air. This system utilises water's high latent heat to absorb a substantial portion of the heat in the air. When water evaporates, a large amount of heat is absorbed, humidifying the air. Figure 2-20 shows the evaporative process, using materials constructed to regulate hot incoming air, and direct evaporative cooling in hot, dry locations would produce a desired rise in humidity (Musa, 2008). Though not effective in humid climates, according to (Adrian et al., 2015).

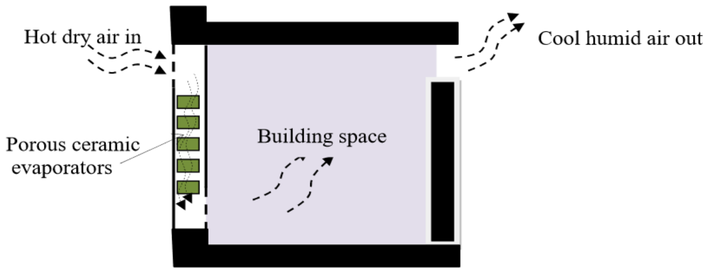


Figure 2-21 Airflow from the ambient to the building through the wall-integrated ceramic evaporators.

- **Phase change materials**

Phase change materials (PCM) can also be employed in construction to minimise internal temperature variations. They store latent heat during a material's transition from a solid to a liquid or from a liquid to a gas. PCM is crucial in refrigeration as it collects heat from the cooling medium (usually water) when they evaporate and releases heat to the environment when they condense. Taking a “fabric first” is a fundamental approach to the energy performance of a building form; Carbon Trust (2012) defined building fabric as the roof, walls, windows, floors, and doors of a building. Improving and maintaining the building fabric offers many advantages and opportunities:

i. Reduced energy and maintenance costs, better temperature control and thermal comfort for occupants, improved productivity
ii. Reducing draughts, solar glare, overheating, colder areas, and noise enhances output and morale.

iii. Lower capital expenditure, efficient, the well-insulated building requires smaller heating and cooling systems, or none.
iv. Better insulation or well-maintained/modified building fabric can increase a building's value and aesthetics.
v. Compliance with regulation.

The design and specification of the building fabric is a major determining factor of energy use in any building. Efficient, the smart design reduces consumption and costs and offers occupants comfort and flexibility. Both ventilation and air conditioning requirements are affected by building fabric; however, heating usually has the largest overall energy cost implication and impact on thermal comfort. Typically, two-thirds of the heat generated in a building is lost through the building fabric (Albatayneh et al., 2018). The rate of heat loss on the buildings depends on:

i. Internal and external temperature difference.
ii. The rate at which the building fabric loses heat.
iii. The amount of fresh (outside) air entering the building either by controlled ventilation or uncontrolled infiltration.
iv. Fabric condition: A well-maintained building loses much less heat. The ability of a fabric to transfer heat is measured and expressed as a U-value. Different fabrics have different thermal (heat transfer) properties.

The U-value of a building element (wall, window, roof, etc.) is an expression of the rate of energy flow (in Watts) for a given surface area (m^2) for a one-degree temperature difference between one side of the element and the other (usually inside and outside). A lower U-value indicates better thermal insulating properties (The Carbon Trust, 2018). As indicated in Figure 2-21, many factors affect the loss and gain of heat in buildings.

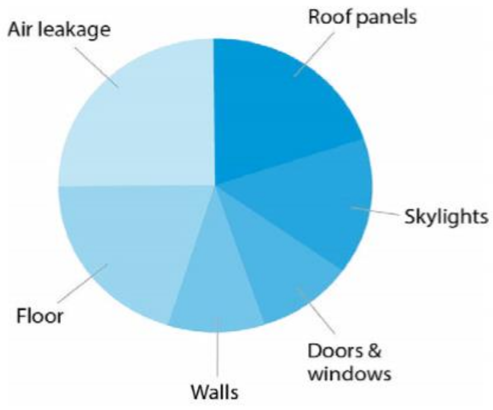


Figure 2-22 Leakages through building elements Source: (The Carbon Trust, 2018).

- ***Leakages in Buildings***

Approximately two-thirds of the heat generated in a building is lost through the building fabric. In contrast, the remaining third is lost through regular ventilation and uncontrolled infiltration in the fabric, causing hot air to enter and cold air to exit the building. In hot and dry climates where cooling is necessary, re-cooling the indoor space due to the influx of external hot air can lead to increased energy consumption. During building operations, common leakages that lead to heat loss from Figure 2-21 amount to 38% of heat lost through ventilation and air infiltration, 26% through windows, 22% through the roof, 9% through walls, and 8% through floors (The Carbon Trust, 2018).

Enhancing the insulation, glazing properties, and Window-to-wall ratio (WWR) are promising solutions for improving the energy performance of buildings in tropical climates, with insulation of the building envelope having the most significant impact on energy savings. Building orientation and the thermal mass of building materials have the least influence on total energy consumption. Thermal bridging should be observed to address leaks in building upgrades; sealing joints and angles in windows, doors, floors, and roofing is important. Proper maintenance of a building's fabric significantly reduces cold air loss and heat gain in buildings in tropical hot/dry climates. The buildings in the climatic zone are less damp due to the low humidity experienced and require ventilation to exchange the hot indoor air. However, before making any changes, it is crucial to understand the HVAC system requirements to ensure they can still effectively cool the building. It's also important to consider the impact on ventilation and take steps to prevent overheating risks (Gupta and Deb, 2023).

- ***Thermal bridging and Insulation of Buildings***

Thermal bridges are weak points in a building's insulation that allow heat to escape from inside to outside. They create cold spots on the interior surface of the building, which can lead to condensation, dampness, and mould growth, reducing comfort and potentially causing structural damage. Thermal bridging is responsible for about 30% of heat loss in a building (The Carbon Trust, 2018).

In cold climates, effective insulation of fabric elements and managing air exchange components of buildings is essential. However, this becomes more challenging in tropical climates due to high daytime temperatures (Kumar & Suman, 2013). Nonetheless, it remains an ideal practice as it not only leads to energy savings but also helps maintain building fabric integrity. It is crucial to properly seal gaps using insulation materials in windows, doors, floors, and roofing at joints and angles (V. Gupta & Deb, 2022). Common insulation materials for sealing building leakages include super-insulated aerogel, expanded polystyrene, extruded polystyrene, foamed polyurethane, and glass fibers; insulation is determined by the thermal resistance or R-value (m2 K/W) (Huang et al., 2020). Before implementing these measures, it is important to understand HVAC requirements for active system services to ensure they can be adjusted to respond to indoor cooling effects or gains. Additionally, the impact on ventilation requirements must be carefully considered, and steps should be taken to mitigate the risks of overheating (Gupta and Deb, 2023).

i. Effective insulating materials can reduce energy consumption by slowing down the rate of heat flow into building mass through conduction.

ii. To achieve maximum effectiveness, they should have low thermal conductivity compared to conventional construction materials.

2.4 Indoor Environmental Quality (IEQ)

Indoor Environmental Quality (IEQ) refers to the conditions inside a building. It encompasses indoor air quality, thermal, acoustic, and visual elements, which impact the well-being and productivity of occupants, as illustrated in Figure 2-18. The relationship between indoor and outdoor environments has drawn attention to air pollution in industrialized countries, affecting both human health and the economy (Mihai and Iordache, 2016). Overheating due to the heating climate is associated with the built-up of high temperatures in the hot/dry zones of the country, and air pollution in buildings is a serious environmental issue of great concern.

Figure 2-23 Indoor Environmental parameters

Ensuring that the parameters stay within defined benchmarked ranges is crucial for elevating occupant satisfaction and overall Indoor Environmental Quality (IEQ). Granting individuals influence over these variables can further enhance occupant satisfaction. It's important to recognize that any alterations to the layout or operational methods can profoundly impact interior conditions, given that IEQ is an integral component of both. A well-devised IEQ plan has the potential to enhance occupants' visual quality, productivity, and comfort, consequently contributing to their overall well-being. This approach can lead to increased productivity and satisfaction while simultaneously reducing energy and healthcare costs and improving overall productivity (Pantelic et al., 2023).

2.4.1 Indoor Air Quality (IAQ)

Indoor Air Quality (IAQ) refers to air quality inside and outside of buildings, focusing on the comfort and health of occupants, as defined by ANSI/ASHRAE 62.2 (2016) rules. Awareness strategies for controlling common indoor pollutants can reduce the risk of health issues. Maintaining adequate indoor air quality (IAQ) in buildings located in hot and dry areas is crucial for students' health and academic performance. The main issues include vaporous organic compounds (VOCs) from furnishings and construction materials, dust collection, and insufficient ventilation (ASHRAE Handbook, 2021).

The process of bringing outdoor air into an indoor space or removing indoor air using natural or mechanical methods is called ventilation. Mechanical ventilation can occur with or without air conditioning. It is used to create airflow and air buoyancy. In hot climates with high temperatures, buildings can be ventilated using active or passive natural ventilation (Bello et al., 2021). Natural ventilation relies on forces like wind pressure, air density variations, and openings like open windows and doors. On the other hand, mechanical ventilation involves using powered equipment such as blowers and fans to introduce or extract air from an interior space, rather than relying on natural forces like wind turbines (ANSI/ASHRAE 62.1, 2016).

Studies have shown that natural ventilation allows air to enter a building and is controlled by building occupants through user-friendly controls (Al-Jokhadar et al., 2023; Pantelic et al., 2023). In hot and dry climates, buildings use air conditioning systems to maintain comfortable interior temperatures during the hot summer. However, these systems can spread dust and other pollutants if not properly maintained. To reduce airborne pollutants, high-efficiency particulate air filters and regular maintenance can improve indoor air quality (ASHRAE,2009). A strategic approach is necessary to address building pollution, mould growth, and indoor air quality (IAQ). This approach should focus on ventilation, moisture control, pollutant management, and regular maintenance to ensure a safe, comfortable, and supportive indoor environment.

2.4.2 Indoor Pollutants (IP)

Indoor areas in buildings in hot, dry climates may face challenges from various pollutants, including indoor ones like CO2. The ANSI/ASHRAE 62.2 standard indicates that CO_2 levels above parts per million (ppm) can have adverse health effects, such as drowsiness, headache, and general body weakness. Pollutants can stem from chemicals and liquids in cleaning products, equipment, and other substances, such as art supplies and lab chemicals, leading to indoor air contamination. Opting for eco-friendly, low-emission construction materials and using them appropriately can play a key role in ensuring better indoor air quality. Additionally, outdoor pollutants, such as vehicle emissions, can impact indoor air quality (ASHRAE, 2009).

Outdoor pollutants such as carbon monoxide (CO) from fuel-burning heaters and appliances, sulfur, nitrogen dioxide, and particulate matter can be more common in buildings located near busy roads or industrial zones. To reduce the impact of these pollutants, using air purifiers and air-filtering plants can be effective. Additionally, volatile organic compounds (VOCs) from paints, cleaning products, and furnishings can also negatively affect indoor air quality. Choosing materials with low VOC emissions and ensuring proper ventilation during and after use can help minimize their impact (US EPA, 2014).

- ***Mould Growth***

Mold growth is usually less prevalent in hot, dry climates due to the lack of humidity. However, it can still occur in localized areas where moisture accumulates, such as around leaky pipes, HVAC systems, or poorly sealed windows and roofs. Moisture control regulates and prevents mould through effective moisture management. This includes repairing leaks promptly from roofs, floors, or openings. Leakages, dampness on walls in water-logged areas, maintaining HVAC systems to prevent condensation, and ensuring proper drainage around the building. Regular inspections can help identify and address potential moisture problems before mould develops. where, when, and how much water and water vapor collect in a building. Mold and other airborne contaminants develop when there is too much moisture (US EPA, 2014).

Humidity Management: Although the ambient climate is dry, indoor environments can sometimes have higher humidity levels due to activities such as cooking, cleaning, and numerous occupants. Dehumidifiers and ensuring good ventilation can help keep indoor humidity levels low, reducing the risk of mould growth (Pantelic et al., 2023).

- ***Particulate matter and dust***

Particulate matter, often termed PM, comprises minuscule particles of solids or liquids suspended in the air. These particles encompass a range of substances, including dust and fog, particularly prevalent in arid, hot environments with high particulate concentrations. When these particles infiltrate indoor spaces through windows and doors, they pose significant risks to human health, environmental integrity, and property infrastructure. The presence of dust indoors can exacerbate respiratory issues and allergies. To mitigate dust intrusion, it is advisable to engage in regular cleaning and utilize doormats. Notably, during Nigeria's dry and chilly season, known as the Harmattan, from late December to early March, a dust storm and strong winds transport particulate matter. This diminishes visibility and can lead to severe respiratory ailments for individuals indoors.

- ***Strategies for Improvement of IAQ in Buildings***

i. Utilize energy-efficient HVAC systems with advanced filters to improve ventilation and enhance indoor air quality (IAQ), while also maintaining temperature control.

ii. Implement a strict maintenance routine for HVAC systems, plumbing, and building infrastructure to prevent conditions that lead to poor IAQ and mould growth.

iii. Install IAQ monitoring systems to quickly detect and resolve air quality issues, promoting a healthy learning environment.

iv. Educate building occupants about the importance of IAQ and best practices, such as opening windows, planting vegetation, minimizing high-VOC materials, and maintaining cleanliness to encourage a collective effort in sustaining a healthy indoor atmosphere (Guevara, Soriano, and Mino-Rodriguez, 2021; US EPA, 2014).

2.5 Learning from Energy Efficiency Regulations in Hot/dry Climates

The term ‘energy efficiency’ is generally used to refer to the use of less energy to achieve the same service or output (NESP, 2015). Over the last few decades, energy efficiency has garnered a fair amount of interest worldwide. Many countries have developed standard requirements in line with global best practices and determined Climate change calls for action since the built environment sector remained significant in addressing the issues (Arup, 2016). Bioclimatic, passive, and energy-efficient designs are some of the technical strategies adopted to reduce global carbon content in the atmosphere produced by the built environment sector (IPCC, 2022). According to Bello et al. (2021), Reducing the amount of energy required for cooling, heating, ventilation, and lighting in buildings to create desirable IEQ conditions requires a strategic approach.

Energy and climatic challenges globally necessitate the need for new ideas and investments in developing energy-efficient strategies in the building industry.

2.5 Summary

Various strategies and principles that utilise the natural elements of the climate to create buildings that are energy-efficient, environmentally friendly, and comfortable are explored in the chapter. By implementing techniques such as proper orientation, shading devices, thermal mass, natural ventilation, and efficient insulation, the harsh climate conditions that challenge human comfort and energy consumption in Nigerian institutional buildings can be mitigated through these strategies. To enhance the physical infrastructure in Nigeria's hot and dry climate, incorporating passive design techniques is crucial; these techniques reduce the need for mechanical cooling and heating systems, leading to significant energy savings and a reduced carbon footprint. ASHRAE-55 Standard and others related were used as reference minimum guide. This aligns with global efforts to combat climate change and promote sustainable development. Passive design not only improves living conditions and building longevity but also offers economic benefits through reduced energy costs. It unlocks the full potential of sustainable architecture in Nigeria's hot and dry climate, creating a responsive and resilient built environment. Additionally, this chapter provides a foundation for assessing thermal performance and energy efficiency in pursuit of a higher quality environment and sustainable building development in the climatic region.

The next chapters shall discuss the processes that justified the selection of the university's case study buildings. They will describe the Architectural features relative to indoor environmental quality and occupant comfort, form performance, and the energy efficiency processes that lead to multi-evaluation in learning environments.

CHAPTER THREE

3. DESCRIPTION OF THE CASE STUDY BUILDINGS, FEDERAL UNIVERSITY BIRNIN KEBBI, NIGERIA.

3.1 Introduction

This chapter discusses the climate of Birnin Kebbi, Nigeria, in relation to buildings. It also analyses the two institutional buildings of the Federal University Birnin Kebbi in the context of design, environmental planning, construction elements, comfort, and energy of the Architectural Studio Complex (1st Case Study) and the Classroom Complex (2nd Case Study). The description includes the architectural design characteristics, form elements, functional spaces, and passive features that will influence the performance and energy efficiency of each building. The chapter also showcases the facilities in relation to the site features and environment, which complements the initial task of building survey and measurement.

3.2 Climate and Average Weather in Birnin Kebbi, Nigeria

Birnin Kebbi, a city in Nigeria, has a tropical savanna climate zone known as *"Aw"* as per global weather standards. This region is one of the five climatic areas in Nigeria that experience high temperatures during the day and significant drops at night. The year-round solar radiation is high, particularly during summers, but sunlight hours decrease during winters (Mobolade and Pourvahidi, 2020; Bena et al., 2019). The average temperature throughout the year ranges from 18°C to 40°C, with occasional drops below 16°C and peaks above 42°C. The different seasons are defined by changes in temperature, humidity, solar radiation, wind pressure, and other climatic factors across the months of the year: hot/wet season, dry/cold season, and wet season. The hot season is often extremely hot with some clouds, while the cold season is relatively dry and cool with increased wind velocity. The wet season is hot and generally cloudy (Weather Sparks, 2023).

3.2.1 Average Temperature in Birnin Kebbi

The average temperature is calculated by finding the midpoint between the highest and lowest temperatures. Figure 3.1 shows that April has the highest average temperature at 34°C, while the lowest average temperature of 25°C is recorded in January and December. During summer, the monthly average temperature is between 30-34°C, and in winter, it is 25- 28 °C.

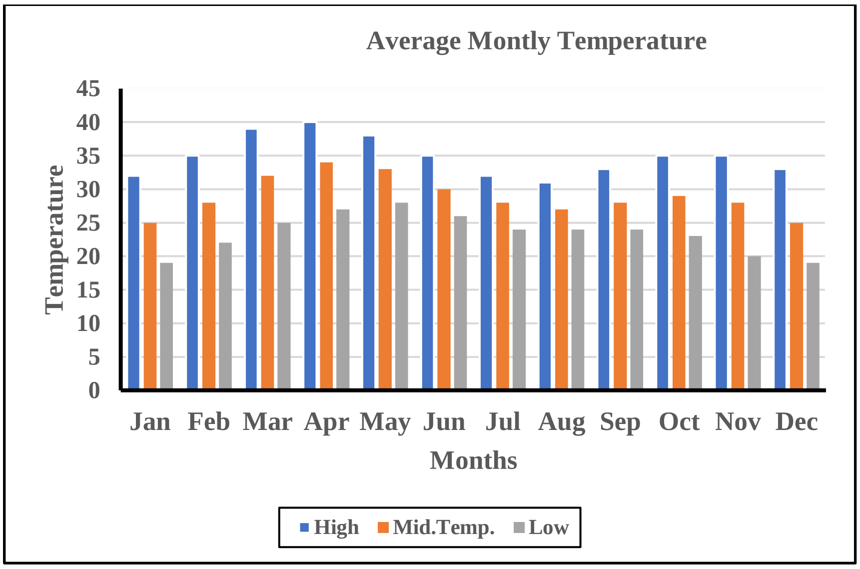


Figure 3-1 Monthly Temperature in Birnin Kebbi.

3.2.2 Hot and Cold Season in Birnin Kebbi

The hot season in Birnin Kebbi starts in March and lasts until May, with an average daily high temperature of over 38°C for 2.1 months. April is the hottest month in Birnin Kebbi, with an average high temperature of 40°C and a low of 27°C. On the other hand, the cold season lasts from early July to mid-September, with an average high temperature of less than 33°C for 2.3 months. January is the coldest month in Birnin Kebbi, with an average low temperature of 19°C and a high of 32°C. The percentage of the sky covered by clouds in Birnin Kebbi, varies significantly throughout the year. The clearest season starts in November and lasts for 4.0 months, ending around March. January is the clearest month in Birnin Kebbi, with a clear, mostly clear, or partly cloudy sky 66% of the time.

The cloudier period starts around March, lasts 8.0 months, and ends in November. May is the cloudiest month in Birnin Kebbi, with the sky being overcast or largely cloudy 68% of the time on average. Birnin Kebbi experiences large seasonal variations in the rainy season. The wet season lasts for 3.9 months, from May to September, with over 41% of the days experiencing rain. August is the wettest month in Birnin Kebbi, with an average of 25.0 days and at least 1 millimeter of precipitation. The dry season lasts 8.1 months, from late September to late May. January has the fewest wet days, with an average of 0.0 days with at least 1.00 millimeters of precipitation (WeatherSparks, 2023).

3.2.3 Relative Humidity

The humidity determines the comfort level of the dew point, it determines whether moisture will evaporate from the skin, thereby cooling the body. In Birnin Kebbi, the monthly average humidity gradually increases during the summer, rising from 40% to 80% over the season. August is the warmest day of the year; the humidity conditions can reach 80%, while on 3 January, the least humid month of the year, February with 13% humidity levels most of the time as illustrated in Figure 3-2.

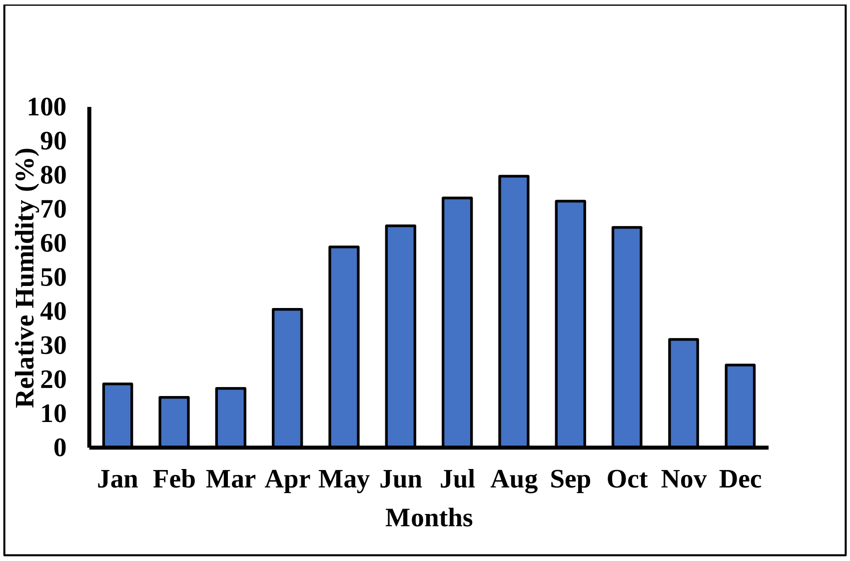


Figure 3-2 Relative Humidity Monthly Average.

3.2.4 Wind Speed

The average hourly wind speed in Birnin Kebbi was based on significant seasonal variation in 2021. The windier part of the year lasts 7.4 months, from late November to early July, with average wind speeds of more than 2.53 meters per second (m/s), see Figure 3-3. The windiest month of the year in Birnin Kebbi is January, with an average hourly wind speed of 3.4 m/s. The less windy time of year lasts 4 months, from early July to late October. The month of the year with low wind speed in Birnin Kebbi is October, with an average hourly wind speed of 1.93 m/s.

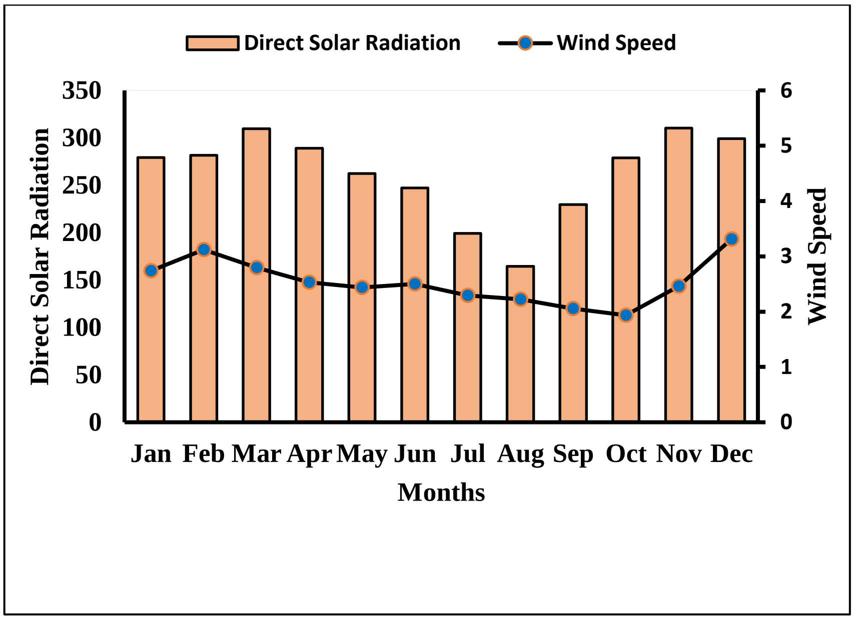


Figure 3-3 Direct Solar Radiation and Wind Speed.

The predominant average hourly wind direction in Birnin Kebbi varies throughout the year. The wind direction is particularly from the south and flows for 6.4 months, from early April to late October, with the lowest percentage in February. The wind is most often from the east for 5.6 months, from late October to early April, with a peak percentage in December.

3.2.5 Solar radiation

Sun radiation determines the sunrise and sunset and is significant in dictating the differences between the day and night hours. Figure 3-3 shows the direct monthly mean solar radiation recorded for the year in Birnin Kebbi, which indicates a total of 3149.67KW/h/m^2 was received in a year. November and March have the highest monthly mean, followed by April with 288.99KWh/m^2. August has the least recorded, with 164.44KWh/m2 for the year. During the summer months of March to June, Birnin Kebbi receives a total average solar radiation of 1,107.7 kWh/m^2. Daily total radiation, according to Isma'il, (2018), Birnin Kebbi receives 5.41KWh/m^2 direct solar radiation per day.

3.2.6 Application of Psychometric Chart in Passive Strategies

The psychometric chart graphically presents the properties of air in buildings, including physical and thermodynamic properties such as dry bulb temperature, wet bulb temperature, humidity, enthalpy, and air density. This information then explains the passive design strategy for ensuring year-round thermal comfort in buildings. The Climate Consultant Version 6 software was used and fed with the *epw*-Weather file of Birnin Kebbi Town. ASHRAE Standard 55 optional guide 2004 using the PMV model was chosen for analysis to ensure the implementation of 100% strategies for the climatic zone, illustrated in Figure 3-4. The boundaries on the psychrometric chart defined the range of outdoor conditions for comfort zones in terms of clothing worn in winter and summer when air movement has the potential to render indoor conditions comfortable in naturally ventilated buildings.

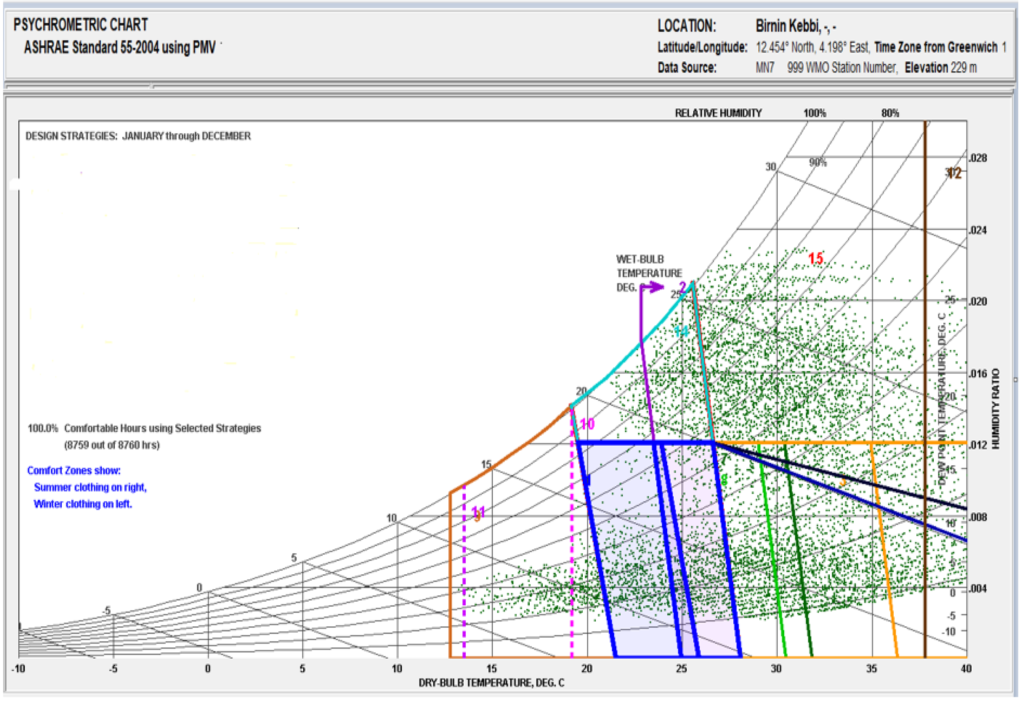


Figure 3-4 Psychometric chart of Birnin Kebbi Town. ASHRAE Standard 55-2004 Using PMV

The psychometric chart indicates that the climate is too hot, with a brown colour indicating high air temperature and a yellow colour indicating low humidity. In summer, the air temperature ranges from 27°C to 40°C, while in the cold/dry winter season, it ranges from 19°C to 32°C. The shaded blue area on the chart represents the comfort zone, showing the appropriate activity and clothing levels for occupants. According to Mushtaha et al. (2021), the psychometric chart provides valuable guidelines for controlling interior air conditions to ensure occupant comfort and energy efficiency. Key guidelines for the dehumidification process include evaporative cooling, sensible cooling, and direct cooling.

- ***Birnin Kebbi Design strategies; January to December***

The following strategies in Table 3.1 are required to achieve 100% Comfort hours, considering 8,759 to 8,760 hours a year. The design strategy for Birnin Kebbi, as illustrated in Table 3.1, indicates that approximately 32.7% of occupants in buildings will find sun shading comfortable, while only 9.7% will find high thermal mass comfortable, 7.6% will find natural ventilation comfortable, and 4.6% will find fan force ventilation comfortable. Comfort levels of 31.4% and 28.8% are attained when utilizing two-stage and direct evaporative cooling strategies. Implementing high thermal mass night flush would make 13.9% of occupants comfortable. Although cooling and dehumidification have a higher percentage of approximately 38.6%, they necessitate substantial retrofitting efforts, which could be pursued if deemed necessary, given the significant technical maintenance and costs involved. However, occupants would experience 16.6% of comfort hours throughout the year if no design strategies were implemented. Comfort hours of passive cooling strategies were rated because of the effective temperatures achieved by using a psychometric chart, which shows Birnin Kebbi's comfort zone. The shading strategy will be implemented in the research for having a substantial percentage (32.7%) and because it requires less technical retrofitting and maintenance initiative.

Table 3.1 Birnin Kebbi Design Strategy and Comfort Hours

Design Strategies	% Comfort hours
Comfort	16.6%
Sun Shading (windows, roof etc.)	32.7%
High Thermal Mass	9.7%
High Thermal Mass Night Flush	13.9%
Direct Evaporative Cooling	28.8%
Two-stage Evaporative Cooling	31.4%
Natural Ventilation Cooling	7.6%
Fan Forced Ventilation	4.6%
Internal Heat Gain	5.6%
Passive Solar Direct Gain High Mass	2.8%
Dehumidification only	7.4%
Cooling and Dehumidification if needed	38.6%

3.3. Case Study Buildings Layout and Environment.

The Federal University Birnin Kebbi permanent site has a measure total area of 2.76 km² and a total distance of 6.69 km. Figure 3-5 illustrates the permanent site of the institution located at latitude 12.45°N and longitude 04.20°E. Specifically, the faculty of environmental science and the two case study buildings on the campus are shown. The Faculty of Environmental Science teaching and learning buildings (studios and Classroom complexes) are central to this research. The facilities are used by the 3 departments (Architecture, Building, and Quantity Surveying).

3.4. Case Study One: Architectural Studio Complex

The Architecture Studios Complex is the first case study building. It was constructed as a dedicated teaching and learning space for Architecture and Environmental Sciences students and completed in February 2019 (Figures 3-5). When viewed in plan, the building has an "E" form shape and comprises two floors. Three departments share facilities for design studio classes. The building location data is given in Table 3.2.

Figure 3-5 Google Earth view of the Permanent site of the University, showing case study Buildings.

Table 3.2 Building Data of Case Study Buildings.

Description	Building Data
Building type	Studio & Classroom Buildings.
Location	Birnin Kebbi town, Kebbi State, Nigeria
Latitude & Longitude	12.3328 ^{0}N, 4.1526 ^{0}E; 12.3334 ^{0}N, 4.1522 ^{0}E
Elevation	213 m above sea level
Year of construction	2019
Number of floors	Ground & 1st floor levels
Facing orientation	North and South
Number of people	250 people at peak occupancy

Figure 3-6 North Elevation of the Architectural Studios Complex.

Figure 3-7 South Elevation of the Architectural Studios Complex.

3.4.1 Building Form and Layout

The Architectural studio complex is a unique and modern building designed for teaching and occupancy purposes. It is the first phase of development on the site, illustrated in (Figure 3-1), with plans for a similar structure in the future. The complex accommodates studios and additional laboratory rooms. The building's form, spatial layout, and arrangement must be planned based on climatic data and passive response considerations to provide comfort to occupants, energy efficiency, and optimal indoor environmental quality. The research by Premrov et al. (2016) and Rashdi and Embi (2016), suggests that the building's surface-to-volume ratio, thermal resistance, and conductivity, not just its orientation, are important factors in reducing energy consumption. Future development plans should prioritize these passive strategies for sustainability.

The building has two levels; the ground floor connects to the first floor with three staircases. Each floor contains two offices, each with two studios and a lab. In addition, there is a public area with a bathroom, hallway, and facility room. The first floor is primarily used for functional learning, with studios serving various academic purposes beyond lectures. For instance, the model-making studio, located in the middle of the two studios, is occasionally used by students for craft projects. Similarly, the computer lab on the top floor is also occasionally used for computer-based lectures. All floors are made of cast in-situ concrete and finished with concrete tiles. Bathrooms and auxiliary spaces are also tiled with a ground-to-ceiling height of approximately 3.5 meters. Three stairs are available, two at the east and west ends and one in the middle of the entry. All three are safe and lead to the first level. The same studios are available on the first floor as the ground floor, and two offices are provided for lecturers at each level.

3.4.2 Building Function and Elements

The studio complex has various utility spaces such as studio/lecture halls, presentation halls, workshop space, offices, storage rooms, data rooms, utility rooms, and auxiliary rooms (refer to Tables 3.3 and 3.4 for more details). These spaces are designed with functionality and dimension in mind. The building's shape is E-linear in geometry, consisting of rectangular studios that can be accessed from the long central passage of the main entrance porch. The studios and workshops have large windows strategically oriented to allow direct entry of solar radiation into the building's interiors (Costa et al., 2019). The large window panel glazing facing the east side creates an aperture for solar heat admittance into the studios.

Table 3.3 Ground Floor; Functional Space of Architectural Studios complex

GROUND FLOOR PLAN				
S/No	**Functional Space**	**L X B (m)**	**Units**	**Area(m^2)**
1	Entrance Porch	5.5 X 4	1	22
2.	Reception Area	8 X 4	1	32
3.	Offices Ground Fl	6 X 5	2	30
4.	WCs to offices	2 X 1.5	2	3
5.	Side Entrances	3 X 2	2	6
6.	General Toilets Area	5.5 X 4	2	22
7.	Central walkway	4 X 33	1	132
8.	Staircase Hall	6 X 4	2	24
9.	Store Office & Data Rm	4.5 X 3.5	2	15.75
10.	Staircase Area Main	8 X 4.5	1	36
11.	Design Studios	16 X 10	2	160
12.	Modelling W/Shop	11 X 8	1	88

Table 3.4 First-Floor; Functional Space of Architectural Studios complex

FIRST FLOOR PLAN				
S/No	Functional Space	L X B (m)	Units	Area(m^2)
1.	General Toilets Area	5.5 X 4	2	22
2.	Central walkway	4 X 33	1	132
3.	Staircase Hall	6 X 4	2	24
4.	Store Office & Data Rm	4.5 X 3.5	2	15.75
5.	Staircase Area Main	8 X 4.5	1	36
6.	Design Studios	16 X 10	2	160
7.	Presentation Hall	11 X 8	1	88

All studio learning spaces must remain cool and ventilated during the day for learning efficiency; therefore, top-hung and three-bottom sliding window panels facilitate the process. The wall colours are light brown, which is pleasant and aid in reducing the overall solar absorption of heat that can result in interior overheating. However, installing about 62 air conditioning units in the complex to maintain thermal comfort for building users is economically costly.

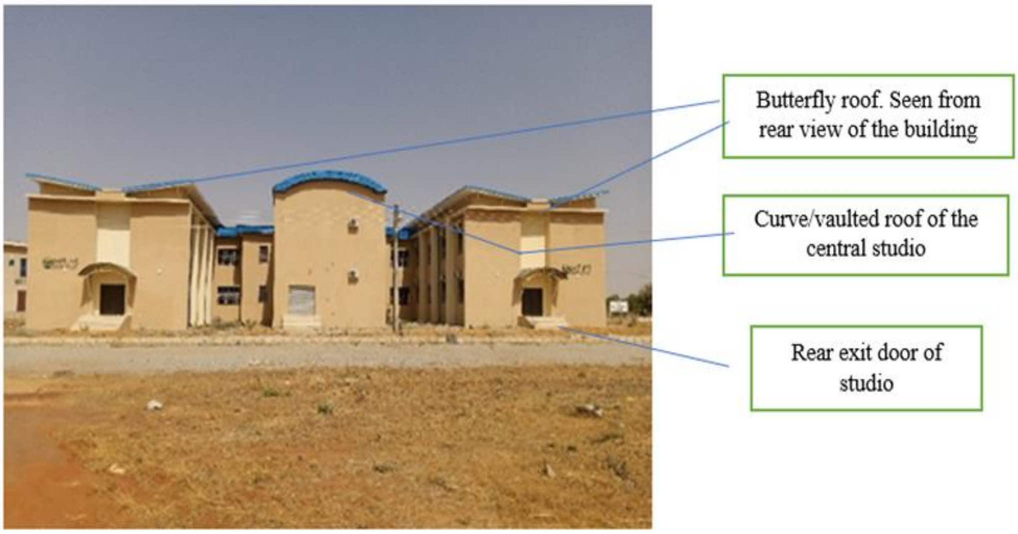


Figure 3-8 South Elevation of the Studio Complex showing structural roofing styles.

The site location of the studio complex proved challenging due to poor orientation energy built up in the interiors, causing discomfort to the occupants. The studio complex has three types of roof construction into shapes: Simple one-way slope, curve and butterfly-shaped roof, and central and end-edged roof gutters positioned for draining water (Figure 3-8). The roof mis made of steel struts members are covered with a blue corrugated long-span Aluminium roofing sheet of 0.45 mm gauge. A parapet wall and a roof gutter maintain easy passage of rainwater.

3.4.3 Passive Design Characteristics of Studio Complex

Many institutional infrastructures across different climatic zones in the country have been built using modern construction materials with high carbon footprints, leading to issues such as indoor overheating and poor building performance. The studio complex building also faces challenges due to its poor orientation during summer periods, which makes the interiors uncomfortably hot for the occupants. Therefore, a passive cooling strategy must be implemented subjectively and objectively to improve the building's comfort performance. The survey findings from the building measurement and instrumentation are the major initial assessment task that will focus on improving the thermal performance and retrofitting of the studio complex of the University and similar infrastructure in the Hot/dry climatic zone.

Before determining the factors that necessitate application of passive strategies to a building, a survey of the building users should be conducted to evaluate any shortfalls of thermal comfort. This subsequent process would involves building instrumentation and measurement methodology. During the survey of the studio complex, several issues were encountered due to inadequate design and construction techniques, as well as the building's susceptibility to climate factors such as solar radiation, which affects indoor temperature. According to Izadyar et al., (2020), the building's geometric shape is critical to the occupants' comfort, with a smaller exterior area on the east and west sides reducing heat loss and minimizing overheating from solar insolation. Zhang et al. (2017); Vethanayagam and Abu-Hijleh, (2019) noted that building geometry and envelope design both play a role in energy efficiency and must be considered during the design, planning, and construction phases to ensure thermal comfort. Efficient form design from the outset of the design process can eliminate the need for heating and cooling (Pan and Li, 2016). Passive maintenance/retrofitting is a viable alternative for existing structures like the studio complex and can be achieved through passive design, as suggested by Nigerian policy documents (Arup, 2016).

3.5 Building Design of Architectural Studio Complex

The Architectural Studio complex building was designed using Building Information Modelling (BIM) software, Autodesk Revit 2021version; due to the absence of designs and schedules from the physical planning unit of the university, the administrative section, saddled with responsibilities of keeping records and timely maintenance of infrastructure. Utilising BIM for the creation of design has been practiced by professionals to improve design, consistent design/construction data, and the development of comprehensive and accurate design documentation (Heaton et al., 2019; Chen and Luo, 2014). The building design was a product of the survey and measurement of the existing information. The designs of the Architectural studio were developed in 2-dimensional and 3-dimensional; the plans, elevations and structural systems in layouts, detailed drawings, sketches, HVAC, and other illustrative specifications were prepared based on on-site measurements and observations to provide data for future design integrations for analysis. (Ho et al., 2013). Tables 3.3 and 3.4 illustrate the studio’s functional spaces.

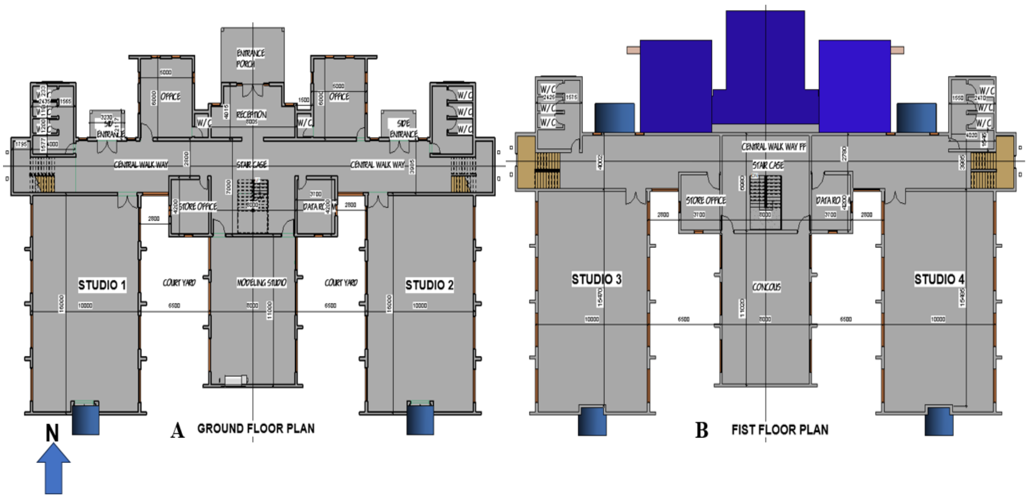


Figure 3-9 Ground Floor plan (A) and 1st-floor plans (B) of the Studio complex.

The building plan shown in Figure 3-9 depicts a typical ground and upper floor layout, apart from the entrance porch, foyer, reception hall, and two offices, the only spaces terminated at the ground floor. All functional spaces on the ground floor are typical of the first floor. The ground floor plan includes two design studios measuring 16,000 x 10,000 mm on the east and west flanks and a modelling studio room space measuring 11,000 x 8,000 mm at the center.

Figure 3-10 South Elevation (C) North Elevation (D)

Figure 3-11 East Elevation (E) and West Elevation (F)

Elevations in Figures 3-10 and 3-11 illustrate the building height and views of the buildings in various directions and the fabric element colours on walls (brown), windows (blue glazing) and roof covering. The roof plan and section in Figure 3-12 demonstrate the building's characteristic roofing styles and uniform structural height.

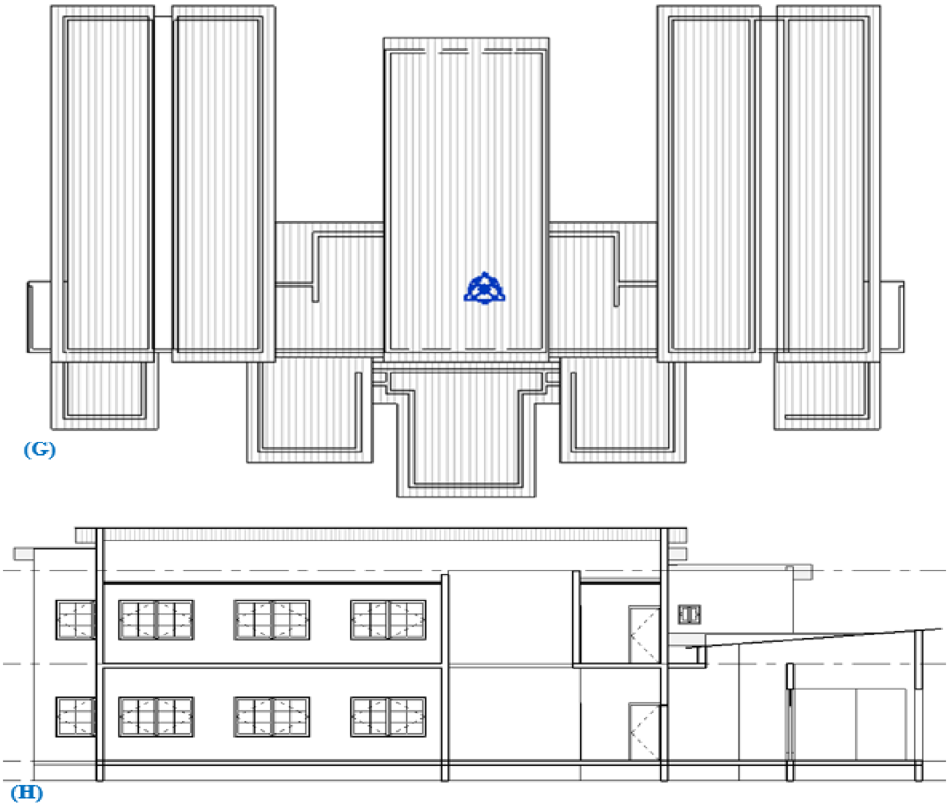


Figure 3-12 Roof Plan (G) and Section View (H)

The goal of the initial task of the building survey was to measure the functional learning spaces with high occupancy where users complained of thermal discomfort; initially, four studios in the building were selected. However, after the initial measurement was completed, it became necessary to choose a (400-level) studio on the first floor for the assessment because all the studios have the same characteristics; this ensured the selection of the studio.

3.5.1 Building Form and Orientation

The form of building performs differently in terms of defending against climate change (Omrany & Marsono, 2016). The studio form is a standalone structure constructed in open-air spaces without close adjacency that can influence air movement, circulation of fresh air throughout the complex and exposure to high solar radiation due to climate and orientation.

3.5.2 Sun path and Solar Angle in Birnin Kebbi

The latitude of a location affects the sun's path, which in turn influences daylight duration and sunlight exposure throughout the year. In summer, the sun rises in the northeast and sets in the northwest at 23.5° along the northern horizon. However, during the winter solstice on December 21. Birnin Kebbi town experiences the rising sun from the southeast at a low angle in the southwest along the southern horizon, and it sets in the southwest. The sun is directly overhead in mid-March. Daylight time is shorter in winter, longer in summer, and almost equal in mid-March. Shadows are relatively longer around the northern orientation axis in summer and shorter in winter.

For example, on June 21, the sunrise is at 05:20 and the sunset is at 18:11, resulting in 12 hours and 52 minutes of daylight. Equally, on December 22, the sunrise is at 06:00, and the sunset is at 17:24, providing about 11 hours and 36 minutes of daylight. During the equinox on March 21, the sunrise is around 05:48 and the sunset is at 17:55, giving 12 hours and 7 minutes of daylight. The sun's path also demonstrates that buildings facing south receive more solar radiation than those oriented in other directions in the given climate. A diagram in Figure 3-13 illustrates the general sun path in Birnin Kebbi for the equinoxes and solstices.

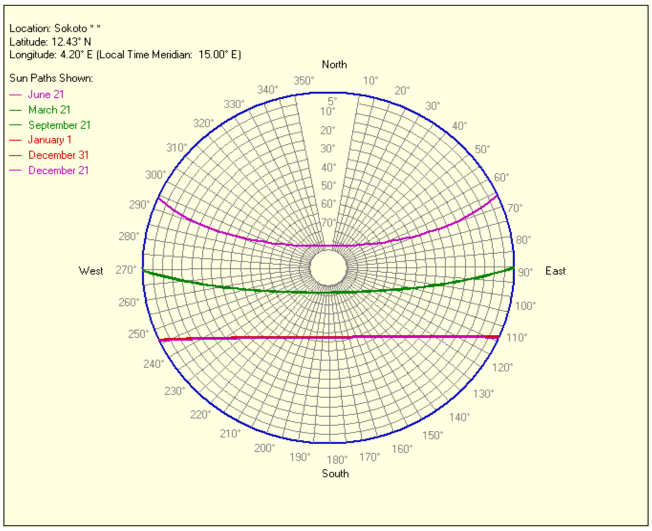
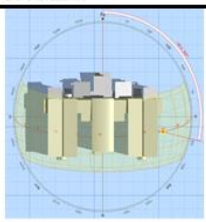
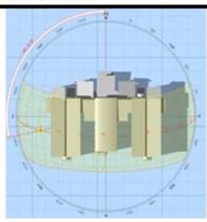
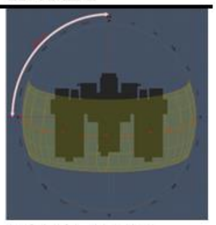
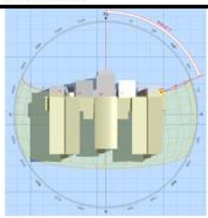
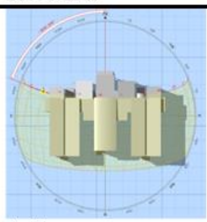
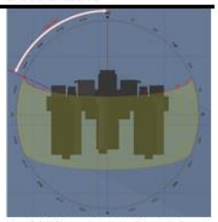


Figure 3-13 Year-round Sun path analysis diagram for Birnin Kebbi, Indicating the solar angle; Equinox, Solstices.

Sun path analysis of the existing Architectural studio complex was carried out based on the current building position. It is relative to realize that solar altitude and angle in Birnin Kebbi are high for most of the year, about 85-87°C during the summer in the month of April. The weather file integrated in the software provides the basis for knowing the effects of solar radiation seen in views of the existing building.

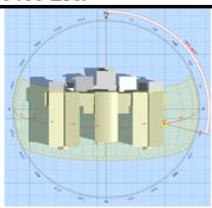
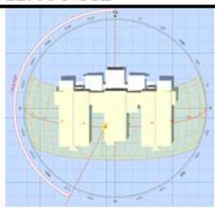
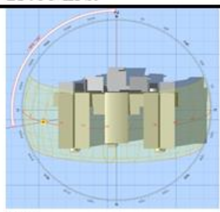
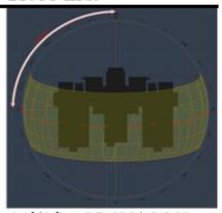
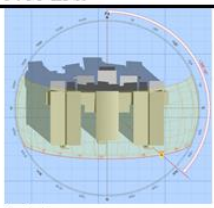
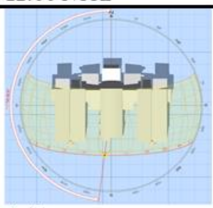
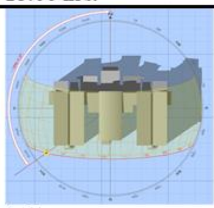
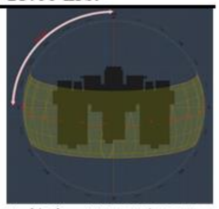
In terms of orientation, this revealed the anticipated solar exposure and the impact of solar radiation at various periods of the day (9:00 am; noon: 15:00 and 18:00 hr) affecting the education building during summer and winter times of the year. Sunrise/daylight and solar alternate angles of the model were visualised under time/hours and rated in the percentage of insolation throughout the seasons and year. To notice the impact of solar insolation angles on the building, solar altitude that determined the annual shadow range on the roof, wall, windows openings, and glazing was provided by the pictorial analysis in tables 3.5(a, b), 3.6. The Andrew Marsh software provided sun path views for the summer solstice, equinox, and winter solstice. The sun path was calculated for the range of 24 hours in a day. Because the sun's impact is during the day, this was considered in the morning, afternoon, and evening (9 am-6 pm).

Table 3.5(a) Sun path diagrams of studio complex in seasons, time, and altitudes (A, B, C and D).

T	9:00 hrs.	12:00 Noon	15:00 hrs.	18:00 hrs.
Equinox - March 20th, 2023.				
A	Azi/ Alt:103.32°/ 45.69°Rise /05:48 / Set: 17:55	Azi/ Alt: -170.16° /77.23°Rise /05:48 / Set: 17:55	Azi/ Alt: -101.53° /41.57° Rise /05:48 /Set: 17:55	Azi / Alt: -89.79° / - 2.02° Rise / 05:48 / Set: 17:55 Daylight: 12:06 Hrs.
T	9:00 hrs.	12:00 Noon	15:00 hrs.	18:00 hrs.
Mid-Summer Solstice: June 21st				
B	Azi / Alt:68.28°/ 49.31°Rise/ 05:20 / Set/18:11	Azi / Alt: -17.09°/78.35°Rise/ 05:20 / Set/18:11	Azi / Alt: -69.39° / 42.61°Rise / 05:20 / Set:18:11	Azi/Alt: -66.34°/1.86° Rise / 05:20 / Set: 18:11 Daylight: 12:51 Hrs.

Tables 3.5 (a, b), and 3.6 present solar shading and sun path analysis of this impact regarding solar radiation on exposed building envelopes and the effects on roofs, walls, and window glazing across the two seasons throughout the year.

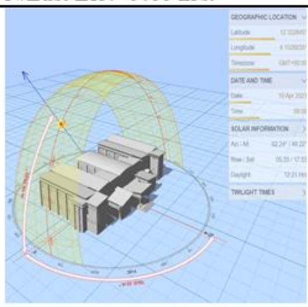
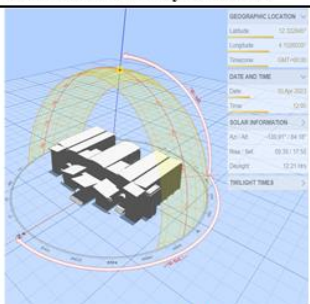
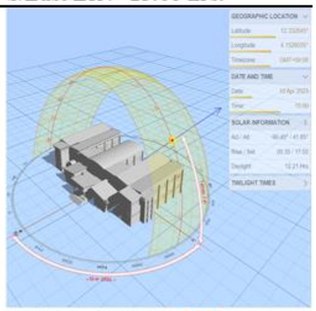
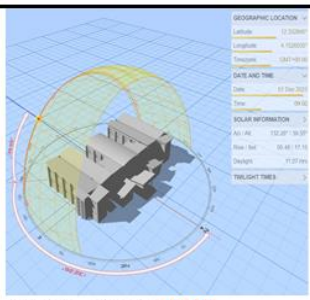
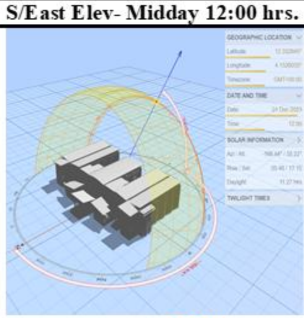
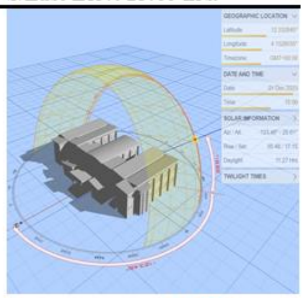
Table 3.6(b) Sun path diagrams of studio complex in seasons, time, and altitudes (A, B, C and D).

T	9:00 hrs.	12:00 Noon	15:00 hrs.	18:00 hrs.
Autumn Equinox: September 23rd				
C	Azi/ Alt:104.80° / 49.51° Rise / 05:32 / Set: 17:39	Azi/ Alt: -153.40°/76.28° Rise / 05:32 / Set:17:39	Azi/ Alt: -99.76°/37.87°Rise/ 05:32 / Set:17:39	Azi/Alt: -88.68°/-5.90° Rise/05:32/Set:17:39 Daylight: 12:07 Hrs.
T	9:00 hrs.	12:00 Noon	15:00 hrs.	18:00 hrs.
Midwinter Solstice - December 22nd				
D	Azi / Alt:132.12° / 36.72° Rise / 06:00/ Set: 17:24	Azi / Alt:-172.83° / 53.96°Rise / 06:00 / Set:/ 17:24	Azi/ Alt: -126.43°/29.77°Rise / 06:00 / Set:17:24	Azi/Alt: -112.18°/-8.98° Rise/06:00 / Set: 17:24 Daylight: 11:24 Hrs.

In addition, the annual percentage shading and total sunlight hours/time were calculated for heights/levels angles and azimuth across the seasons.

In Table 3.4 (A-D), the sun path diagrams of the building were simulated using the online application ‘Andrew-Marsh’ to indicate the position of the sun during Equinox, solstices and display the degree rise, azimuth angles and daylighting time for sunrise and sunset in summer and winter seasons (Andrew Marsh App, 2022). The highest and lowest solar altitude of 78.35°/42.61° at 12:00 (noon) and 15:00hrs are observed in mid-summer (Table 3.4B), while the highest/lowest sun altitude in mid-winter is 53.96° and 29.77° respectively (Table 3.4D). Determining the solar angle is important to protect building elements from exposure on the hottest days of the year and to plan for shading.

Table 3.7 Sun Path Positions and Time during the Hottest Day (E) and coldest Day (F) of the Year.

T	N/East Elev- 9:00 hrs.	S/East Elev- Midday 12:00 hrs.	S/East Elev- 15:00 hrs.
April 10th E	 Azi / Alt: 92.24° / **49.22°** Rise / Set: 05:35 / 17:55 Daylight: 12:21 Hours	 Azi / Alt: -139.92° / **84.18°** Rise / Set: 05:35 / 17:55 Daylight: 12:21 Hours	 Azi / Alt: -90.45° / **41.85°** Rise / Set: 05:35 / 17:55 Daylight: 12:21 Hours
T	**N/East Elev- 9:00 hrs.**	**S/East Elev- Midday 12:00 hrs.**	**S/East Elev. 15:00 hrs.**
December 1st F	 Azi/Alt: 132.26° / **39.55°** Rise / Set: 05:48 / 17:15 Daylight: 11:27 Hours	 Azi / Alt: -168.44° / **55.22°** Rise / Set: 05:48 / 17:15 Daylight: 11:27 Hours	 Azi / Alt: -123.46° / **28.61°** Rise / Set: 05:48 / 17:15 Daylight: 11:27 Hours

The impact of solar radiation and its positions at different times on the building in April’s hottest day of the year is shows on table 3.5 (E-F) at 09:00, 12:00, noon and 15:00 hours, the Sun angle/altitude is 49.22° while the azimuth is 92.24°. At noon, the Solar altitude reached the year's highest of 84.18° at an azimuth angle of -139.92°. Lastly, at 15:00 hours, the Sun altitude is 41.85°, and the azimuth is -90.45°. The Sun rises at 05:35 and sets around 17:55 on April 10, considered to have the longest daylight of 12:21 hours and the hottest day of the year in the hot/dry climatic zone of Birnin Kebbi, Nigeria.

During the winter, the Sun is at a lower angle (ranging from 28.61°-55.22°) and has a much shorter daylight period of 11:27 hours than the hottest summer day, resulting in less direct sunlight hitting the building at different times, see (Table 3.5E and F). This could lead to a decrease in the building's heating and may require more artificial lighting to maintain the same level of illumination. Furthermore, the lower Sun angle during the winter could result in less solar energy available in solar energy systems.

3.5.3 Artificial Ventilation in Studio

During the visit, the entire building's facades revealed that mechanical cooling devices (AC units) are regularly operated indoors to provide cooling and improved ventilation. Figure 3-14 illustrates the outside western elevation view of the studio, the installation of split AC components on the wall, the inside effects of sunlight and solar heat, and how the windows remained exposed, unshaded, and unprotected from the solar insolation. The Sun path result analysis indicates that the studio building has a poor orientation, with East and West-facing windows.

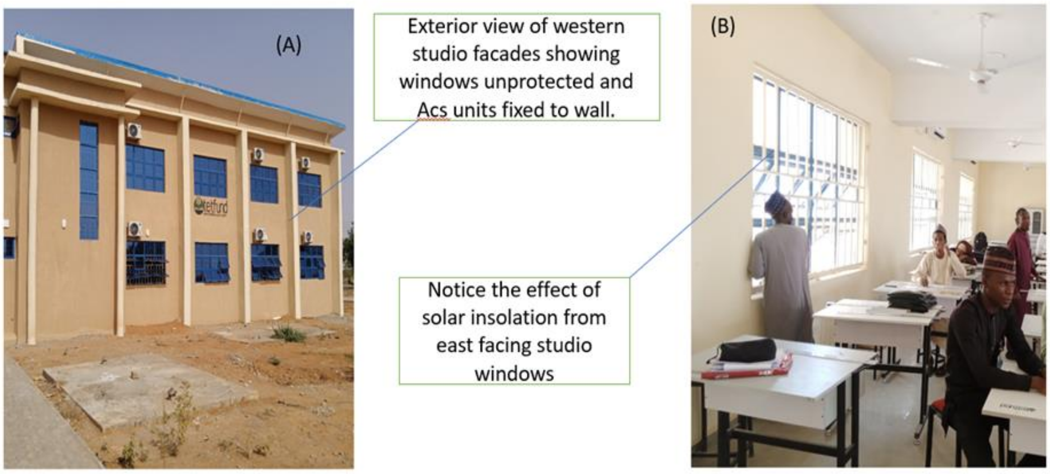


Figure 3-14 Impact of Solar insolation in Architecture Studio complex building.

Solar radiation critically affects the studio structure; this prompted the assessment to propose quantifying solar radiation's impact on the studio building under existing conditions. The provision of shade components helps block high-angle incidence of solar radiation during the late morning to early afternoon and midday periods, curtailing the impacts of undesired solar radiation on buildings. Making shading equipment effective in tropical areas is necessary to measure sun insolation. (Kiamba, 2016; Ghabra, 2017).

3.5.4 Orientation and Effect on Natural Ventilation of Studio Complex

According to Omrany and Marsono (2016) and Warner (2011), it's recommended to have a good orientation building structure with longer sides facing North and South and shorter facing towards the east and west cardinal points, also normal while positioning windows and a significant portion of the building's facade to face north and south for ventilation. This approach is particularly effective in hot and dry tropical climates, providing solar protection and optimal natural airflow for ventilation of the building's interior. This method reduces the amount of solar radiation affecting the indoor space, lowering the air temperature inside the building. Buildings facing east receive morning radiation, while those facing west receive afternoon radiation. Additionally, green spaces, such as trees, bushes, and grass, have a cooling effect on the surrounding air temperature through evapotranspiration. Previous studies have shown this (Zhang et al., 2014; Szokolay, 2008).

3.5.5 Studio Functional spaces

The studio's complex has 24 functional spaces with a total volume of 5018.97m^2 and a total floor area of 1455.71m^2, comprising the first and ground floor levels. Only the 4 studio rooms were used for teaching, learning, and design, and would be considered for assessment on passive strategy, as illustrated in Table 3.7.

Table 3.8 Schedule of Accommodation for Architectural Studio Complex.

SN	Space Name	Volume (m^3)	Floor Area (m^2)	Extern Wall (m^2)	Win. Open (m^2)	Wall/Win. Area (m^2)
1	Main Entr. Hall	147.83	94.16	40.31	2.40	16.80
2	Central PassGF	548.06	156.59	131.08	4.80	27.31
3	Staff Off 1 GF	120.07	60.03	37.70	6.00	6.28
4	Staff Off 2 GF	120.07	60.03	37.70	6.00	6.28
5	Gen. Toils GF1	49.25	14.07	38.59	1.44	26.80
6	Gen. Toils GF2	49.25	14.07	38.59	1.44	26.80
7	Staircase Hall1	162.29	23.18	52.88	3.56	14.85
8	Staircase Hall2	162.29	23.18	52.88	3.56	14.85
9	WC Off. 1	14.79	4.23	5.28	0.36	14.67
10	WC Off. 2	14.79	4.23	5.28	0.36	14.67
11	Equip. rm GF1	38.85	11.10	23.45	2.40	9.77
12	Equip. rm GF 2	38.85	11.10	23.45	2.40	9.77
13	Studio 100LGF	561.29	160.37	147.07	38.34	3.84
14	Studio 200LGF	561.29	160.37	147.07	38.34	3.84
15	Model Rm GF	308.12	88.03	105.03	29.70	3.54
16	Central Pass FF	548.06	156.59	131.08	4.80	27.31
17	Gen. Toils FF1	52.73	28.15	41.49	1.44	28.81
18	Gen. Toils FF2	52.73	28.15	41.49	1.44	28.81
19	Equip RM FF1	46.28	11.23	26.41	2.40	11.00
20	Equip RM FF2	46.28	11.23	26.41	2.40	11.00
21	Studio 300L FF	661.85	160.37	195.22	34.56	5.65
23	Studio 400L FF	661.85	160.37	195.22	34.56	5.65
24	Entrance Porch	52.09	14.88	38.36	27.27	1.41
	TOTAL	**5018.97**	**1455.71**	**1582.04**	**249.97**	

The four studios have the same dimensions (16000mm x 10000mm) and a floor area of 160.37m2 each. Other auxiliary learning spaces were a computer laboratory (first-floor level) and a modelling workshop on the ground floor (11000mm x 8000mm), which were occasionally used by students of the three faculty departments during organised/specific lecture periods.

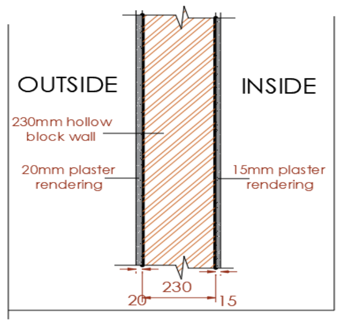
3.5.6 Building Construction Elements

Building elements are considered the basic components of built form: walls, floors, roofs and opening/fenestrations, glazing, foundations, and partitions (Omrany and Marsono, 2016). Building materials/elements were measured, and thermal conductivity for each was calculated and used as input parameters for building assessment. Table 3.8 presents the properties of building construction materials in terms of thickness, thermal mass, and U-values of the studio complex.

i. Wall Elements

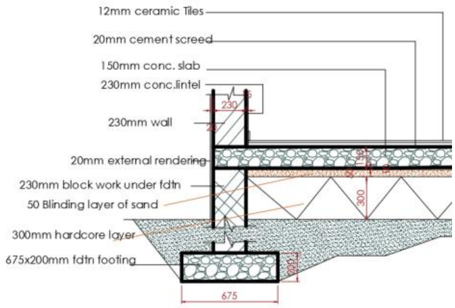
Concrete materials were used for wall construction. Sandcrete blocks (450mm x 225mm x 225mm and 450mm x 150mm x 225mm) with quality characteristics resist damage, rust, and decay. Based on specifications, vertical walls were constructed using the frame structural block filling, bonding, and laying through the reinforced concrete columns and beams (horizontal and vertical). Both internal (partitions) and external Walls are of the same size and plastered with cement and sand mortar in varying ratios (1:5), and the internal plaster is 15-18mm, while external plaster thickness of 20-25mm was considered, illustrated in (Table 3.2). The studio's external walls form more than 74% of the space. The walls were rendered in light-brown paint, a neutral colour similar in tone to the natural ground soil and considered moderate heat conductivity depending on the composition's thermal transmittance (U-value). Implementing light-colored finishes on walls can help distribute natural light deeper into the spaces.

Table 3.9 Specifications of Construction element (Author field survey).



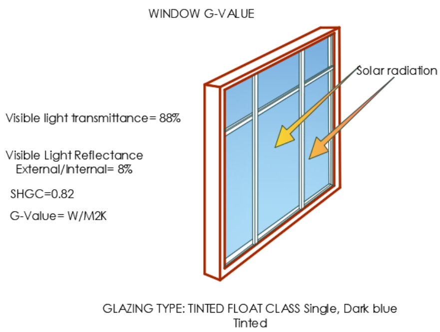
WALL DETAILS

Material Thickness	270mm
Thermal mass CM (J/K)	138.00
U-Value (W/m^2K)	1.43



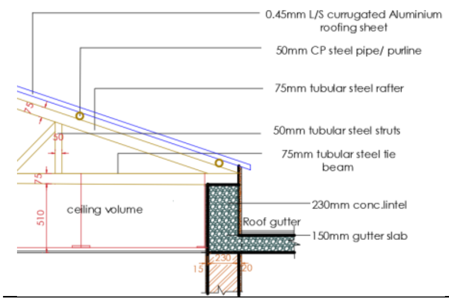
FLOOR SLAB DETAILS

Material Thickness	600mm
Thermal mass CM (J/K)	187.74
U-Value (W/m^2K)	1.71



WINDOWS DETAILS

Material Thickness	0.6mm
g-value=0.48; Transmittance e (T)	0.76
U-Value (W/m^2K)	5.69



ROOF DETAILS

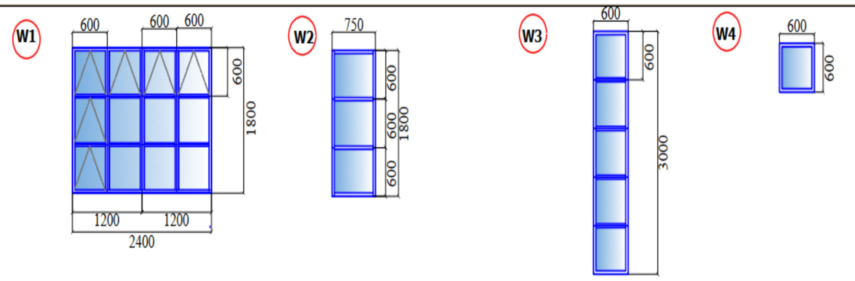
Material Thickness	--
Thermal mass CM (J/K)	6.55
U-Value (W/m^2K)	7.14

Concrete suspended floor: 190 mm thickness, U-value-1.91 W/m^2K and thermal mass J/K.

ii. *Floor Elements*

The structural surfaces installed on the ground level are the floors, the initial structural unit to be built for any building construction; the foundation offers a secure ground floor. It is a structural unit that evenly distributes the load from the superstructure to the underlying earth and solid base (Konis et al., 2016)The studio's floors were built using various materials, including concrete slabs, tiles, and cement/sand mortar. At first-floor levels, where they acted as the ceilings and roofs for the ground space, studio floors are horizontally built and attached to the foundation (Table 3.2). Numerous passive cooling methods use flooring and foundations in buildings. (Konis et al., 2016; Omrany and Marsono, 2016; Wan Yusoff and Sulaiman, 2014).

Table 3.10 Windows Schedules.

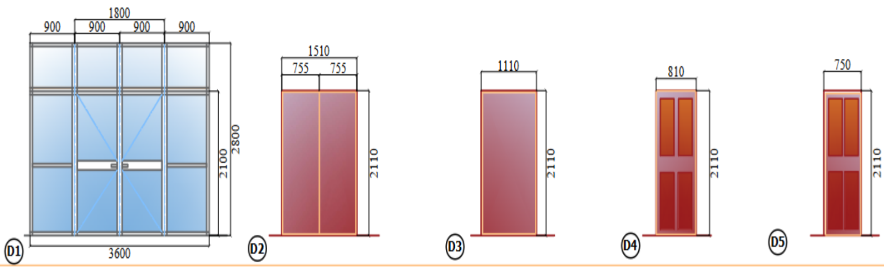
WINDOWS SCHEDULE				
DRAWING				
LOCATION	Studio Rooms, Computer Lab, Central Passage and Modelling Room	Offices and Lobbies	Stair case	Toilets and stair case hall
QUANTITY	48	28	2	18
SPECIFICATION	Alluminium Anodized Single-top hung Glazed Projected Panel Window	Alluminium Anodized Single-top hung Glazed Projected Panel Window	Alluminium Anodized Single-Glazed fix Panel	Alluminium Anodized Single-Glazed Projected Panel

i. *Windows and Doors Elements*

Openings are provided in the walls for ventilation and access to the building. The building's most common type of opening is the door (internal and external). The studio complex has been fitted with aluminum anodized panel windows as openings for ventilation and light with a 6mm blue glazing area in various window types, sizes, and specifications, Table 3.9. Window openings were frequently fitted with glazing. However, glazing plays a significant part in building energy management because of its effects on the passage of solar radiation through the interior spaces (Omrany and Marsono, 2016).

The thermal transmittance, solar transmittance, and air leakage as on frame and mechanical installation airtightness all affect the windows in terms of energy efficiency. The glazing system can be regarded as a key factor in determining the window's energy performance among all the other factors discussed (Al-Tamimi, 2022; Lee et al., 2013). There was less access to the 4-studios (focal spaces), and one door was made provisional. On the ground floor, studios have 2-doors (internal and external), while at first floor levels, only 1-door opens to the studio space. See Floor plans, Figure 3-9 (A and B). The doors have uniform specifications in Table 3.10 (2100mm x 1800mm). Single swing, dark-brown colour, steel solid-filled core frame doors panels were the only occupants' access to the studios, and there were no exit doors on the first floors, which would constitute a serious safety problem.

Table 3.11 Doors Schedules.

DOORS SCHEDULE					
DRAWING					
LOCATION	Main Building Entrance Door	External Side Entrances and Computer Lab/ Modeling W/S	Internal Studio's Entrance Doors	Offices Doors	Toilet Doors
QUANTITY	1	4	8	6	20
SPECIFICATION	Alluminium Glazed Panel Doors, 2x2-leaf Double Swing	External Steel Panel Single way Double leaf Door 1510x2110	Internal Steel Panel Single way One leaf Door 1110x2110	Wooden flush Single way One leaf Door 810x2110	Wooden flush Single way One leaf Door 750x2110

Similarly, each studio room has 8 windows with dimensions (1500 x 2400 mm) at east/west elevations, for natural ventilation and lighting. Although the passive approach encourages the utilisation of daylighting as a strategy through the design by the provision of large windows, but the poor orientation may affect the comfort performance. The studio Windows are fully projected at 90° horizontal angle opening. Opening and closing of windows are important aspect of occupant's operable behaviours, it allows transmission of fresh air and circulate in terms of needs. While natural cross-ventilation may be challenging due to the east-west orientated windows, interior shading solutions such as blinds, curtains, or shades to manage sunlight and glare during peak sun hours can be a shading solution, insulation of the leakages arising from window frames and utilizing mechanical ventilation systems to improve air circulation and promote cooling airflow, an operative control mechanism should be put in place in this regard. Currently, each studio room has 6 air conditioning units, and 6 fans units installed for cooling and ventilation, these mechanical gadgets consume substantial energy. Although tall windows can encourage stack ventilation, where hot air rises and exits through openings at higher levels, creating a natural airflow, the studio window's orientations remain a problem to this process. Shading devices such as overhangs and high-performance insulated glazing would protect the exposed windows and walls from direct sunlight, reducing solar heat gain (Lee et al., 2013).

ii. Roof Structural Element

The architectural studio comprises different roofing styles; the entrance porch and other ground-floor offices have flat roofs, while the computer laboratory has a domed roof. The studio's plank (located at east and west) is shaped like a butterfly. The roofing material that covers 95% of the total roof area is a blue-coloured long-span corrugated aluminium sheet with a high u-value. Roslan et al. (2016) study describes roofs as the topmost part of a building's structure that covers its highest surface. Roofs are the most crucial component of a structure exposed to intense solar radiation and high emissivity levels. During the day, the roof absorbs heat, increasing the indoor temperature and affecting the occupants' comfort levels. Roof shading is a crucial passive approach that can reduce solar insulation minimize heat, and when the roof is shaded, it improves cooling, as it receives the most significant solar radiation during the year.

3.5.7 Landscaping and Outdoor Environment

The surrounding environment has less vegetation than usual. The new layout site was cleared during the studio construction, and no plans were made for landscaping to provide shade over time. Research suggests using passive solutions to improve outdoor areas, such as planting native, drought-tolerant plants to reduce the need for excessive irrigation and maintenance. Trees and vegetation placed strategically around the complex can provide shade and enhance the microclimate. This approach can improve thermal comfort and create a more pleasant environment in the courtyard (Abdulkareem, 2016; Zhang et al., 2014; Lee et al., 2013).

3.6. Case Study Two: The Classroom Complex

The Classroom Complex is a two-story building located at the Faculty of Environmental Sciences layout building facility on the permanent site of the Federal University Birnin Kebbi. It was chosen as a case study building to analyse a typical learning environment with unique teaching layouts that can be considered under the influence of climate and environmental factors. The selection process was because different learning spaces have varying functional learning roles. The classroom complex is a two-storey structure constructed and used as a learning space where students receive lectures, basic knowledge demonstrations and skills during normal class teaching hours. The occupants' activity levels can affect thermal comfort indices, indoor air quality, and overall health and well-being. Although the building is constructed with modern materials and fitted with a mechanically ventilated gadget that consumes energy, the building's forms and geometry can influence the provision of comfort and indoor environmental quality. A review of the building can provide useful data for intervention, allowing researchers to investigate the implication of form shape factor and performance in ensuring thermal comfort provision in higher educational buildings located in hot/dry climatic zones.

3.6.1 Building Site, Land Use, and Layout

The layout site is still being developed; new buildings will be constructed based on the campus's feature development plans. Currently, the buildings within the faculty layout are isolated and far apart, and the surrounding layout has little or few traces of natural landscape elements. This indicates the deserving need for future growth when more departments are established.

3.6.2 Building Form and Function

The classroom complex is a one-storey building with a typical floor-level design. It is a prototype building that has been constructed in multiple locations on the university's permanent site campus. The building has a central courtyard that links the movement to various functional spaces. The building envelope consists of walls made of concrete Sandcrete blocks, glazed windows, and a metal roofing structure and sheet. It was occupied in 2020. The building is occupied by students for 8 to 9 hours based on the nature of environmental sciences courses teaching modes. Understanding the occupancy, functional utility and design characteristics of the classroom learning space. Each classroom has a minimum of 60 to 100 students' capacity. Figures 3-15 (A and B) shows the North and South elevation views and Figures 3-16 (C and D), East and West elevations of the building show the east and west façade with fewer windows and how the windows of the building are recessed. but the wall frame does not provide adequate solar shading as intended. The classroom complex has installed mechanical ventilation system, such as AC units and fans mostly operated by occupant during summer. However, the windows are still opened when electricity supply seizes. Occupants are allowed to operate these gadgets for cooling when required. The building heavily relied on mechanical ventilation during summer to improve indoor comfort.

Figure 3-15 North Elevation (A) and South Elevation (B) of the Classroom Complex FES, FUBK Birnin Kebbi.

Figure 3-16 East Elevation (C) and West Elevation (D) of the Classroom Complex.

3.7 Building Design and Functional Spaces

The classroom complex is located about 400 meters from the Architectural studio complex, within the same faculty layout. Table 3.11 presents the location details. In Figure 3-17 (A and B), the classroom complex covers an area of 1459.35 m^2, considering the combined space at first and ground floors. Each floor level has 3-learning spaces. There are four classrooms of equal size, each with a capacity of 100 students. In addition, there is a seminar and presentation classroom with a floor area of 114 m2. The functional spaces on both levels are evenly distributed. The building survey and measurement aspects for the study informed the decision to produce the design of the classroom complex in 2D and 3D. Subsequently, the lack of availability of deeper building information necessitated the design production from Figure 3-17 to 3-21.

Table 3.12 Building Data

Building- Classroom Complex, Dept of Architecture, FES	
Range	592.72
Latitude	12.33°N
Longitude	4.15°E
Altitude	213.57m

Table 3.13 Functional Spaces of the Classroom Complex.

SN	Functional Spaces	Volume (m3)	Floor Area (m^2)	Extern Wall (m^2)	Win. Open. (m^2)	Wall/Win. Area (m^2)
1	Entrance Po.	292.45	35.66	100.4	67.5	1.49
2	Stair Hall	132.86	16.2	66.76	9.45	7.06
3	Central Ps GF	461.17	112.48	163.5	77.4	2.11
4	Class rm A GF	590.4	144	98.8	10.8	9.15
5	Class rm Ps A	164	40	57.94	10.08	5.75
6	Class rm B GF	590.4	144	98.8	10.8	9.15
7	Class rm Ps B	164	40	57.94	10.08	5.75
8	Pres. RM GF	470	113.9	45.2	8.1	5.58
9	R.Gen WC GF	140.94	34.38	50.09	3.67	13.65
10	Staff Wc RGF	70.78	17.26	10.2	1.2	8.50
11	Urinal RM GF	79.45	19.38	10.15	0.68	14.93
12	Ramp GFF	386.44	47.13	37.41	4.5	8.31
13	L.Gen WC GF	140.94	34.38	50.09	3.67	13.65
14	Staff Wcs LGF	70.78	17.26	10.2	1.2	8.50
15	Urinal rm LGF	79.45	19.38	10.15	0.68	14.93
16	Class rm D FF	590.4	144	98.8	10.8	9.15
17	Class rm Ps D	164	40	57.94	10.08	5.75
18	Class rm C FF	590.4	144	98.8	10.8	9.15
19	Class rm Ps C	164	40	57.94	10.08	5.75
20	Seminar rm FF	470	113.9	45.2	8.1	5.58
21	R. Gen WC FF	140.94	34.38	50.09	3.67	13.65
22	Staff Wcs RFF	70.78	17.26	10.2	1.2	8.50
23	Urinal rm RFF	79.45	19.38	10.15	0.68	14.93
24	L.Gen WC FF	140.94	34.38	50.09	3.67	13.65
25	Staff Wcs LFF	70.78	17.26	10.2	1.2	8.50
26	Urinal rm LFF	79.45	19.38	10.15	0.68	14.93
	TOTAL	**6395.2**	**1459.35**	**1367.19**	**280.77**	

3.7.1 Building Form and Elements

The classroom building was composed in a simple rectangular form, with utility spaces arranged within a central courtyard. The two-level height structure (ground and first floors) has 24 typical functional spaces connected by a staircase and a ramp. The staircase is accessed from the main entrance while the ramp is positioned deep inside the building; table 3.12 shows the functional spaces schedule of accommodation. According to NIBS, (2012), building form comprises the building elements, such as the foundation and floor, walls, roof windows, and doors, the significant features of form fabric elements that were systematically assembled, creating an indoor environment, and defining the functional spaces. A building envelope is made of elements which separate the indoor and outdoor environments of a building (Jha and Bhattacharjee, 2018).

3.7.2 Materials and Construction Technology

University buildings in the country are constructed using modern materials such as cement and concrete. The concrete materials are used to make blocks, structural foundation, floors, and walls. The floor slabs are made of reinforced lightweight concrete and finished in various materials, such as ceramic tiles, cement screed, and terrazzo. The floor finishes are made to withstand high traffic and water usage in traffic areas like lobbies, passages, and in toilets floors and walls. Ceilings are constructed using particle boards, PVC sheets, or pilasters of Paris (POP). Walls are made of 150-250mm thick concrete hollow blocks and are often rendered with cement plaster and painted in desired colours. The thickness of the partition walls is the same as the external walls, and the roof is pitched with structural steel members in the required specifications. The roofing is covered with 0.45mm thick blue colour long span aluminium roofing.

i. Floors

The total building floor area of the structure is 182.58m^2. The ground floor functional spaces are similar in size to the first floor, as shown in Figure 3-17. The structural floors are made of concrete cast in situ and finished with ceramic tiles as the top surface of the finished floor.

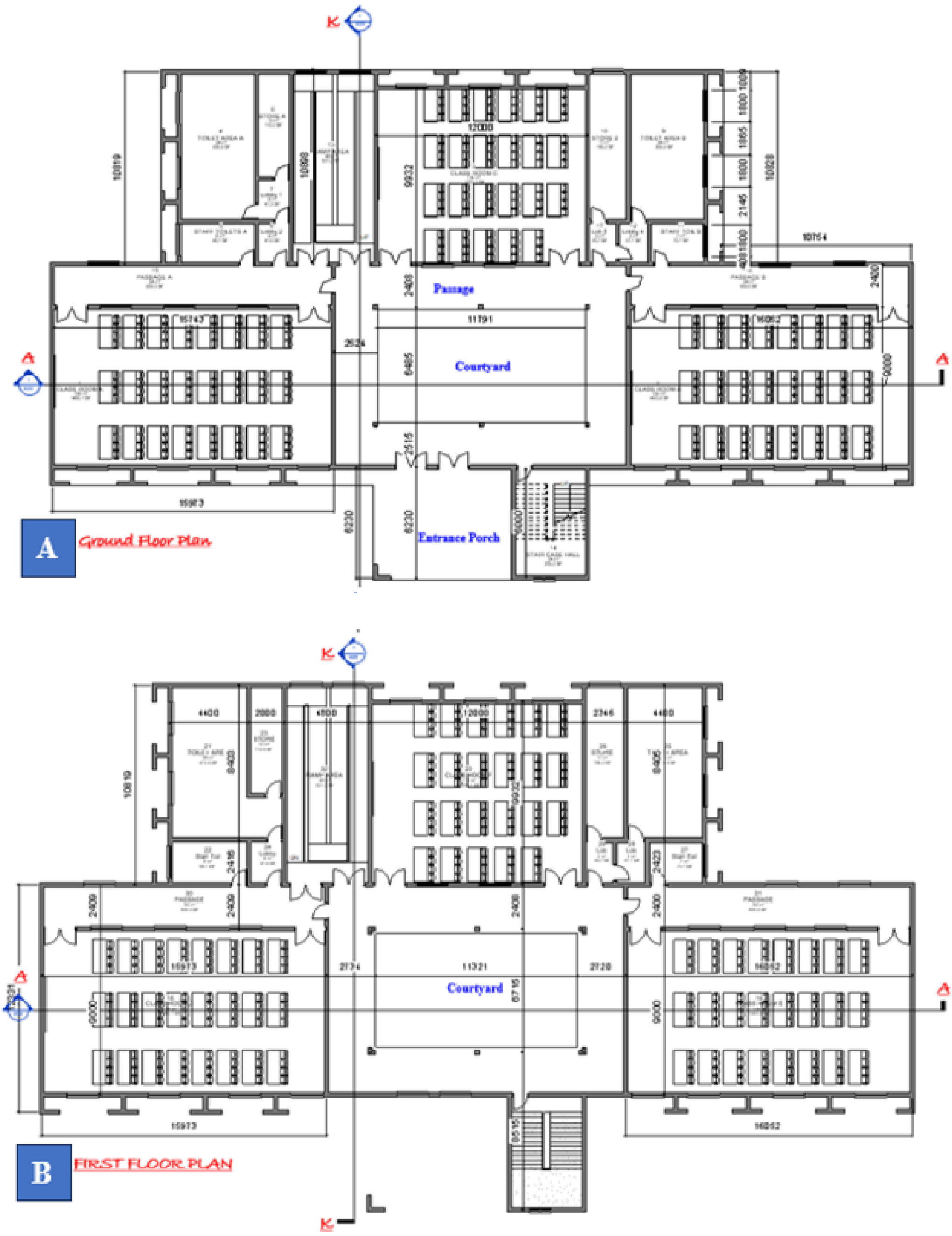


Figure 3-17 Ground Floor (A) and First Floor (B) Plans of the Classroom complex with functional units.

ii. Roof

The pitch roofing system of the classroom complex was a steel structure and roofed with a blue corrugated long-span Aluminium roofing sheet, as illustrated in Figure 3-18 specification. The roof covers an area of 762.80m^2 Table 3-12. The effectiveness of a roof in reducing the temperature inside a room is expressed by its composition of materials, physical properties and colour. Roofs of buildings in hot/dry climates are shaded, and light colour materials are selected or applied to the surfaces to improve the indoor environmental quality, and provide thermal comfort by lowering the interior temperature, as explained by (Koumbem et al., 2021).

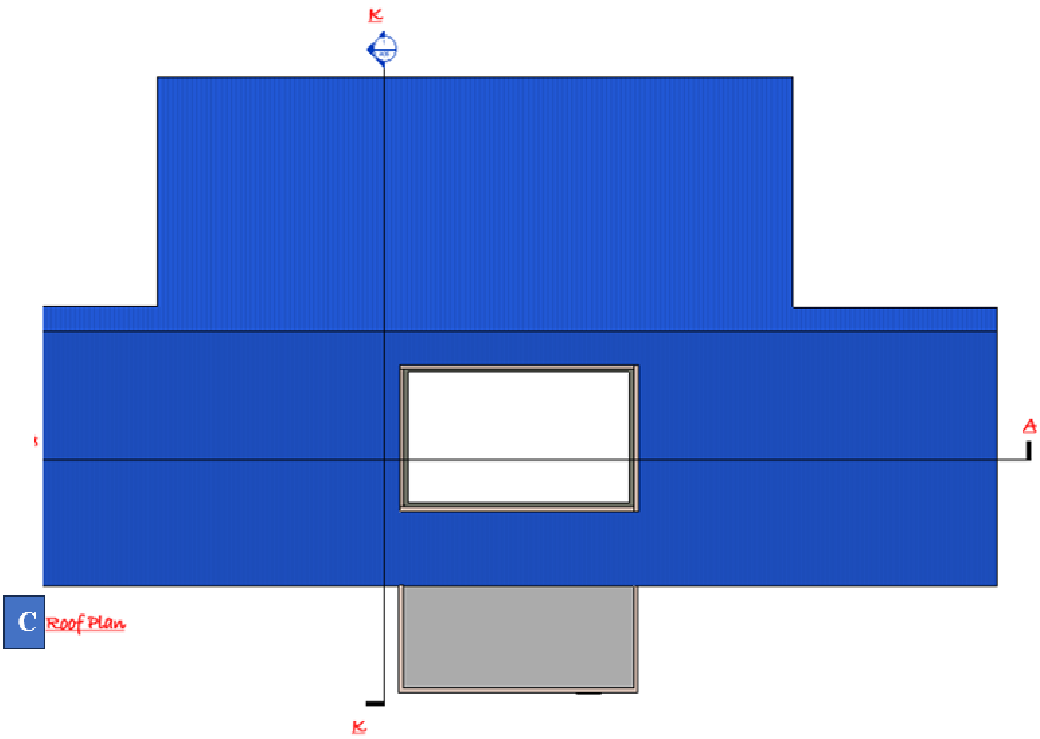


Figure 3-18 Roof Plan (C), with blue Colour long span Aluminium roofing cover.

The upper floors of the building from the section A-A and K-K were made up of reinforced concrete cast in situ in line with the structural specification thickness as illustrated in Figure 3-19. The 4-classroom seen in the section at the ground and first floor levels were finished with light brown colour tiles with median energy conduction characteristics as related by research (Pal et al., 2020).

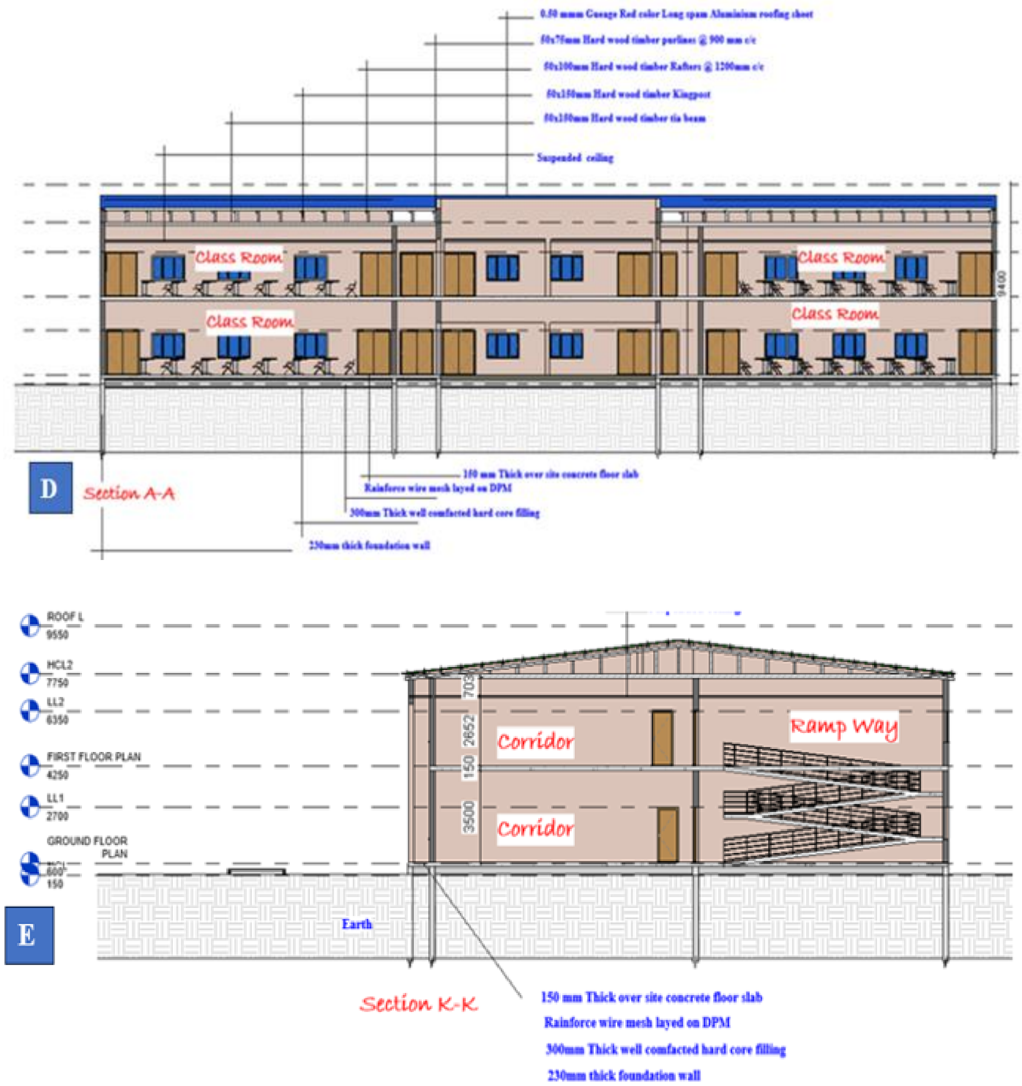
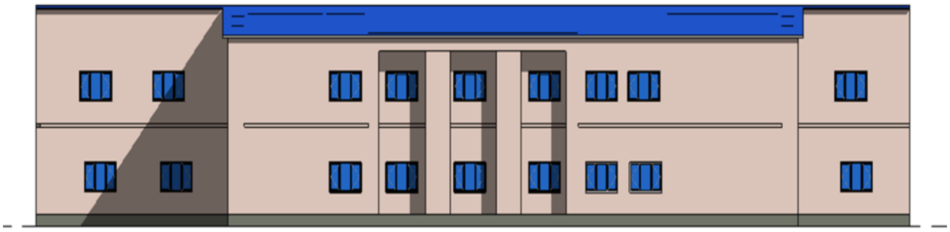


Figure 3-19 Section A-A (D), and Section K-K (E) of the classroom complex.

iii. Walls and Elevations

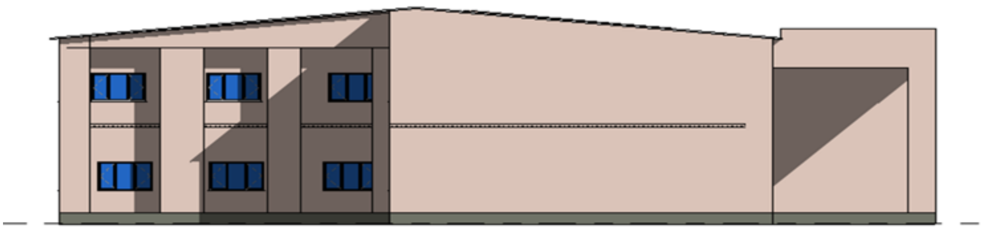
The building design demonstrates the elevations in Figures 3-20 and 3-21 and other physical elements. The structural wall of the building was constructed with hollow Sandcrete concrete blocks with specification 230x230x450mm, bonded with cement mixture plastered and rendered in a light brown colour with lower heat conduction. The structure has a total external wall area of 1367.19m^2, highlighted in Table 3.12 schedule specification of the construction elements. Walls make the vertical enveloping shell of the building, rendering externally and internally reduced. It's used for demarcating indoor spaces and creating a volume as it serves as a surface for fixing openings and orifices.

F South Elevation

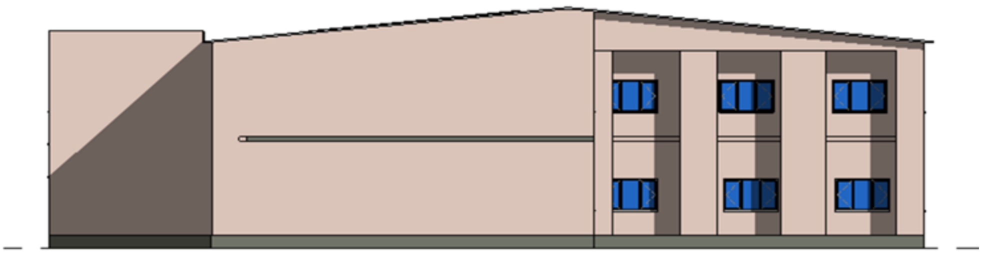


G North Elevation

Figure 3-20 South (Approach) Elevation (F) North (Rear) Elevation (G).



H West Elevation



I East Elevation

Figure 3-21 West elevation (H) and East Elevation (I).

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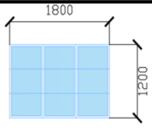
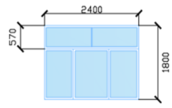
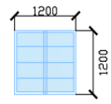
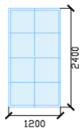
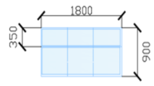
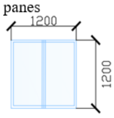
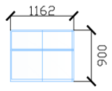
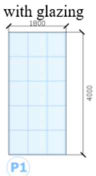
Wall insulation, together with other components of building elements such as floors and ceilings, helps to reduce heat loss and gain through conductivity without affecting the form's physical appearance and improving comfort (Vijayan et al., 2022). Light-colored exterior walls and white roofs help to reduce cooling loads (US-DOE, 2002; Montenegro et al., 2012).

iv. Windows

The building has 68 Aluminium windows with glazed fitted portions in various sizes and modes (swinging and projected). Two large panel windows, 2400 x 1800 mm and 2100 x 1200 mm are fixed along the two staircase walls. The six classrooms at the ground and first floor levels have 36 windows, each with six windows of 1800x1500mm dimension. The building has 280.77m^2 of window area.

Table 3.14 Windows Schedules and Specifications

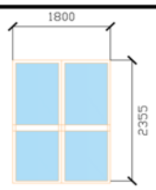
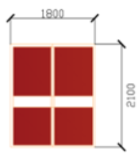
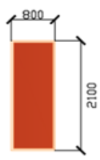
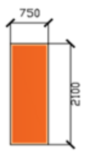
WINDOWS SCHEDULE					
Drawing	 W1	 W2	 W3	 P2	 W4
Location	Classrooms/P/Rooms	Classroom passages	Entrance passage	Staircase/Ramp	Store Gen. Toilets
Quantity	**40**	**6**	**4**	**2**	**12**
Specification	Aluminium frame swinging panel windows with 9-glazing panes	Aluminium top fixed, down projected frame windows with glazing	Aluminium 2-swinging panels frame windows with glazing	Aluminium fixed panel glazed frame windows	Aluminium top/down hung projected panel with 15-glazing panes
Drawing	 W5	 W6			
Location	Stores	Urinals	Panel Frame		
Quantity	**2**	**4**	**1**		
Specification	Aluminium 2-swinging leaf glazed panel	Aluminium top-hung projected glazed panel	Aluminium fixed panel with 15-glazing panes		

Classroom windows are swinging types, opening at 90º maximum to their fixed frame. The 0.4 to 0.6mm navy-blue colour glazing reduces the transmissive (g-value) properties of the window, considering the net glazing area. Table 3.13 illustrates the types, specifications, and material composition of the windows, sizes, and windows-to-wall ratio. Windows are considered as one of the most important components of the building envelope, reflecting their impact on energy use and thermal comfort in space; their openings can modify the intensity and distribution of daylight to create appropriate luminous desirable to classroom environments (Okpalike et al., 2022; Zomorodian et al., 2016; Baker and Steemers, 2013). Windows of the classrooms are considered as important elements and significant in the assessment process and Architectural interventions of the learning environment due to their function for the provision of ventilation, natural lighting, and thermal comfort and operability associated with the opening mode to the users of indoor space.(Ramirez and Hamza, 2018).

v. Doors

There were 12 external doors serving as entrance and exit doors and 24 internal door frames fixed in the building complex that provide access to the utility spaces. All the external doors of the building are double steel panels/swings of 2100x1800mm. The internal doors are solid core wooden flush doors with specified dimensions of 2100x850mm and 2100x750mm, respectively. The door schedule of the classroom complex is illustrated in Table 4.3 and Table 3.14. Door frames in buildings are significant fenestrations that have an impact on the ventilation, indoor air quality and energy efficiency in terms of the user operatives and material U-value (Baker and Steemers, 2013).

Table 3.15 Doors Schedules and Specifications

DOORS SCHEDULE				
Drawing				
Location	**D1** Entrance Main	**D2** Classroom Main	**D3** Office/Stores	**D4** Toilet
Quantity	**2**	**12**	**12**	**8**
Specification	Aluminium frame panel doors with 4-glazing panes	Steel frame panel doors	Wooden Flush doors	Wooden Flush doors

3.7.3 Landscaping and Outdoor Environment

Prior to the beginning of the construction, all landscape elements such as trees, vegetation, shrubs, and hardscape were removed from the site as is commonly practiced. An aerial view of the site depicted in Figure 4.5 confirmed a significant absence of vegetation within the building layout.

3.7.4 Passive Design and Environmental Construction Strategies

The classroom complex is a free-standing structure independent of other structures within the layout site. There is an absence of adjacency buildings to provide shade. The climate's heating characteristics and vegetation's absence negatively impact the surrounding environment. Although the building is favoured with good orientation, serious landscaping by planting trees with large foliage on the East and West sides can remedy the situation to reduce the impact of solar insolation on the building fabric. Poor design and construction also can negatively impact building performance and the well-being of occupants. Therefore, it is desirable to implement passive climate control systems to maintain the classroom facility to improve its performance in preventing indoor overheating. Cooling techniques such as shading can significantly improve the environmental performance of the university learning environment.

3.7.5 Sun path, altitude, and Building orientation.

The Sun path analysis of the classroom building illustrates the sun's movement, angle, sunrise, and sunset across the months and seasons in the year and time. Tables 3.15, 3.16, and 3.17 show these indices of daylight actions on solstices and equinox. The summer period begins from March to June. During these months, buildings in the climate receive higher daylight over longer hours than in winter. Sunrise and sunset result in the formation of night and day.

The Sun's positions in the sky at different times of the day, hitting the building in April (the hottest month) exerts impact beginning from 09:00 hours, when the Sun is at a lower angle/altitude of 49.22°, while the azimuth is 92.24°, at noon. The Solar altitude reaches the year's highest of 84.18° and on the azimuth angle of -139.92°. At 15:00 hours, the Sun altitude is 41.85°, and the azimuth is -90.45°. The Sun rises at 05:35 and sets around 17:55 on April 10, considered the longest day with the daylight of 12:21 hours; this day was also the hottest day of the year.

Table 3.16 Sun path diagrams of classroom complex Equinox and Mid-summer A - B.

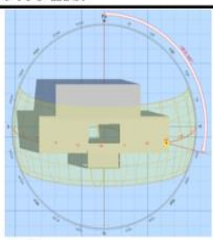
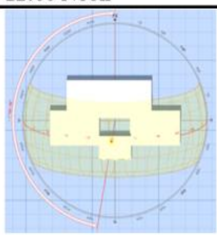
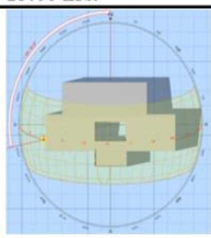
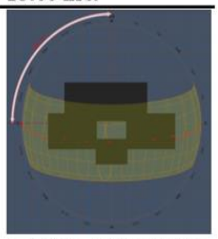
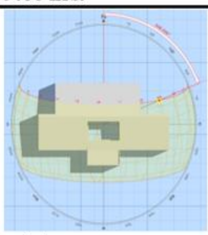
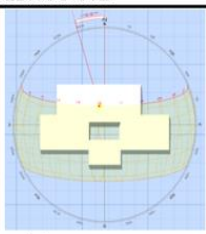
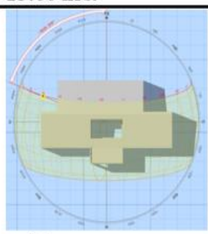
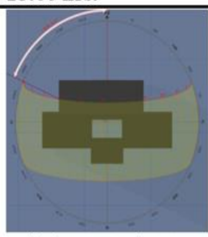
T	9:00 hrs.	12:00 Noon	15:00 hrs.	18:00 hrs.
Equinox - March 20th.				
A	Azi/ Alt:103.32°/ 45.69° Rise /05:48 / Set: 17:55	Azi/ Alt: -170.16° /77.23° Rise /05:48 / Set: 17:55	Azi/ Alt: -101.53° /41.57° Rise /05:48 /Set: 17:55	Azi / Alt: -89.79° / 2.02° Rise / 05:48 / Set: 17:55 Daylight: 12:06 Hrs.
T	9:00 hrs.	12:00 Noon	15:00 hrs.	18:00 hrs.
Mid-Summer Solstice: June 21st				
B	Azi / Alt:68.28° / 49.31° Rise/05:20 / Set/18:11	Azi / Alt: -16.97° / 78.36° Rise/ 05:20 / Set/18:11	Azi / Alt: -69.39° / 42.61° Rise / 05:20 / Set: 18:11	Azi/Alt: -66.34°/1.86° Rise / 05:20 / Set: 18:11 Daylight: 12:51 Hrs.

Table 3.17 Sun path of classroom Autumn and Mid-Winter seasons (C – D).

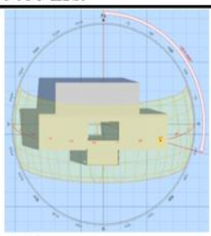
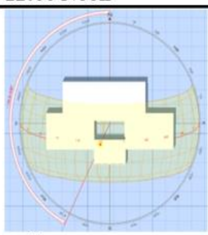
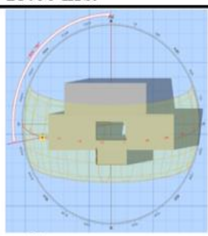
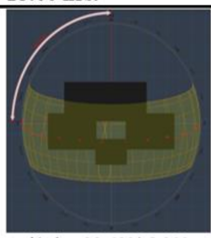
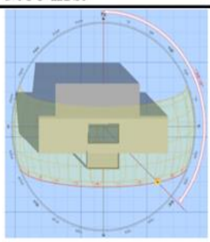
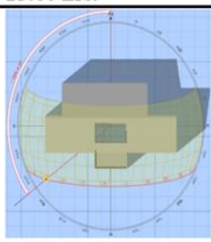
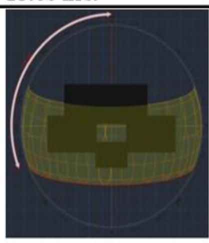
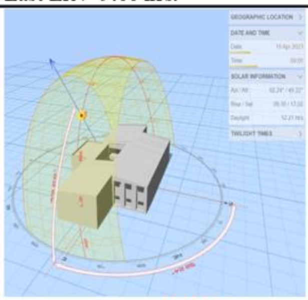
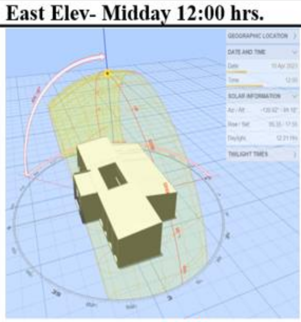
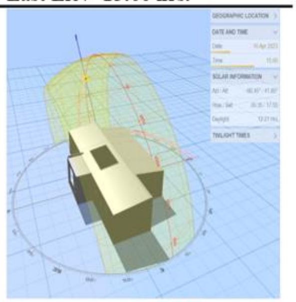
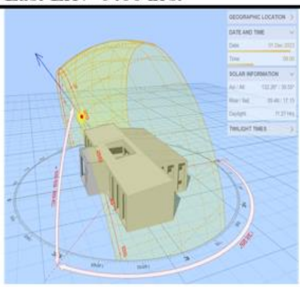
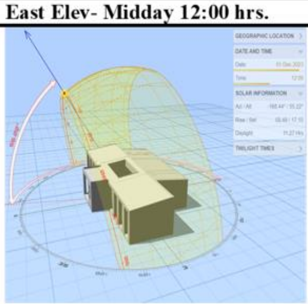
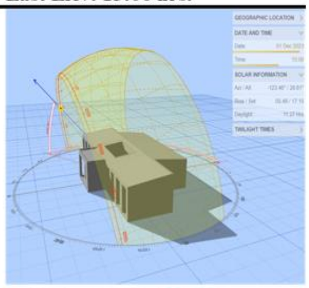
T	9:00 hrs.	12:00 Noon	15:00 hrs.	18:00 hrs.
Autumn Equinox: September 23rd				
C	Azi/ Alt:104.80° / 49.51° Rise / 05:32 / Set: 17:39	Azi/ Alt: -153.40°/76.28° Rise / 05:32 / Set: 17:39	Azi/ Alt: -99.76°/37.87° Rise/ 05:32 / Set: 17:39	Azi/Alt: -88.68°/-5.90° Rise/05:32/Set:17:39 Daylight: 12:07 Hrs.
T	9:00 hrs.	12:00 Noon	15:00 hrs.	18:00 hrs.
Midwinter Solstice - December 22nd				
D	Azi / Alt:132.12° / 36.72° Rise / 06:00/ Set: 17:24	Azi / Alt: -172.83° / 53.96° Rise / 06:00 / Set:/ 17:24	Azi/ Alt: -126.43°/29.77° Rise / 06:00 / Set: 17:24	Azi/ Alt: -112.18°/-8.98° Rise / 06:00 / Set: 17:24 Daylight: 11:24 Hrs.

Table 3.18 Sun path during the hottest/coldest day of the year, (E – F).

T	East Elev- 9:00 hrs.	East Elev- Midday 12:00 hrs.	East Elev- 15:00 hrs.
April 10th			
E	Azi / Alt: 92.24° / **49.22°** Rise / Set: 05:35 / 17:55 Daylight: 12:21 Hours	Azi / Alt: -139.92° / **84.18°** Rise / Set: 05:35 / 17:55 Daylight: 12:21 Hours	Azi / Alt: -90.45° / **41.85°** Rise / Set: 05:35 / 17:55 Daylight: 12:21 Hours
T	**East Elev- 9:00 hrs.**	**East Elev- Midday 12:00 hrs.**	**East Elev. 15:00 hrs.**
December 1st			
F	Azi/Alt: 132.26° / **39.55°** Rise / Set: 05:48 / 17:15 Daylight: 11:27 Hours	Azi / Alt: -168.44° / **55.22°** Rise / Set: 05:48 / 17:15 Daylight: 11:27 Hours	Azi / Alt: -123.46° / **28.61°** Rise / Set: 05:48 / 17:15 Daylight: 11:27 Hours

The Sun is at a lower angle (28.61°- 55.22°) on the coldest winter day in December. It has much lower daylight of 11:27 hours than the hottest summer day, resulting in less direct sunlight hitting the building at different times, which decreases the heating of the building but results in increased use of artificial lighting to maintain indoor illumination level. (Andrew Marsh App, 2022). Proper building orientation can prevent indoor overheating caused by solar heat gain into building interiors and reduce fabric exposure to solar radiation. Shading roofs and windows is effective for hot, dry tropical climates.

3.8 Summary

The two case study buildings of the Architectural studio and the classroom complex are discussed in the research in terms of their physical nature, form design/geometry, and construction features of the two learning environments. The focus was identifying the problems observed during the initial survey visit and determining the building's condition through physical measurements. The chapter also highlights the framework for achieving the study goal towards implementing passive techniques effectively. The case studies were analysed based on several factors, including their relationship with climate, environment, building form, orientation, construction features, building elements, functional spaces, zoning considerations, and unique building features. A detailed reproduction of the building designs in BIM software was accomplished to obtain building data and information for further analysis. The design and construction attributes of each building were analysed in detail to provide valuable insights on utilizing passive strategies to reduce indoor overheating in learning spaces and ensure a comfortable environmental context.

CHAPTER FOUR

4. POST-OCCUPANCY THERMAL COMFORT EVALUATION: CASE OF ARCHITECTURAL STUDIO COMPLEX, FEDERAL UNIVERSITY BIRNIN KEBBI, NIGERIA

4.1 Introduction

The chapter focuses on the assessment and evaluation of the Architectural studio building. Post-occupancy evaluation is accomplished through subjective and objective processes. The subjective evaluation was conducted by conducting interviews and administering a questionnaire to the building's managers and occupants to gather information about the indoor environmental quality (IEQ), user thermal comfort, and other environmental factors of the classroom complex case study. However, the objective evaluation process involved measuring the physical parameters of the structure through surveys, instrumentation, and experimentation. Data loggers were used to collect thermal comfort indices for analysis to ensure that the indoor environmental quality meets the minimum standards. This is crucial for the overall well-being of the building's occupants, including students and staff in the learning environment.

4.2 Instrumentation and Measurement of Environmental Data

The initial experimental measurements were conducted for all studios (100 to 400 levels) on the ground and first floor. After analysing the results from SunCast software simulations, the 400L studio (first-floor level) was selected because of its full occupancy status all the time; it also has unique attributes that can apply to the rest studios. The experiment was staged for the whole season, covering both hot (summer) and cold (winter) periods. The hot season is from March to June, with April being the hottest month, when the outdoor temperature can reach approximately 40°C. The cold season is from December to February, with December being the coldest month, when the outdoor temperature can reach

26°C. Netatmo smart data logging devices monitored microclimate conditions, including air temperature, mean radiant temperature, air velocity, relative humidity, CO2 emissions, lighting, and noise levels throughout the day for several months. The ASHRAE 55-Standard document for occupancy guided our measurements. Measuring temperature, humidity (indoors), air quality, carbon dioxide (CO_2) concentration, noise levels, and wind velocity (outdoors) using a NETATMO Smart home weather measuring device. During the experimental study period, considerations were made on the need for occupancy factor, the hottest month of the year; April was considered the reference month for the overheating analysis in this study to develop an understanding of students' attendance impact on indoor and outdoor environmental conditions. The results are required while students are in sessions in the studios 24/7. The calibration process of NETATMO and HOBO onset devices calibration process of occurred with this moderation.

4.1.1 NETATMO Smart Weather Device

The NETATMO Smart Weather device consists of two devices that can connect to additional units and require a high-speed internet connection. However, it cannot be used with public hotspots. The device supports Wi-Fi 802.11 b/g/n (2.4GHz) and has open/WEP/WPA/WPA2-personal security. The wireless connection between modules can cover up to 100 meters without obstacles. The Indoor Module Weather Station measures indoor comfort parameters, noise and pollution levels through its sensors and can be used at homes, in offices, or in classrooms (Figure 4-1).

The Weather Station's wireless Outdoor Module provides real-time weather data with sensor measurements at the doorstep. The technical specifications of the data logging devices are in Table 4.1.

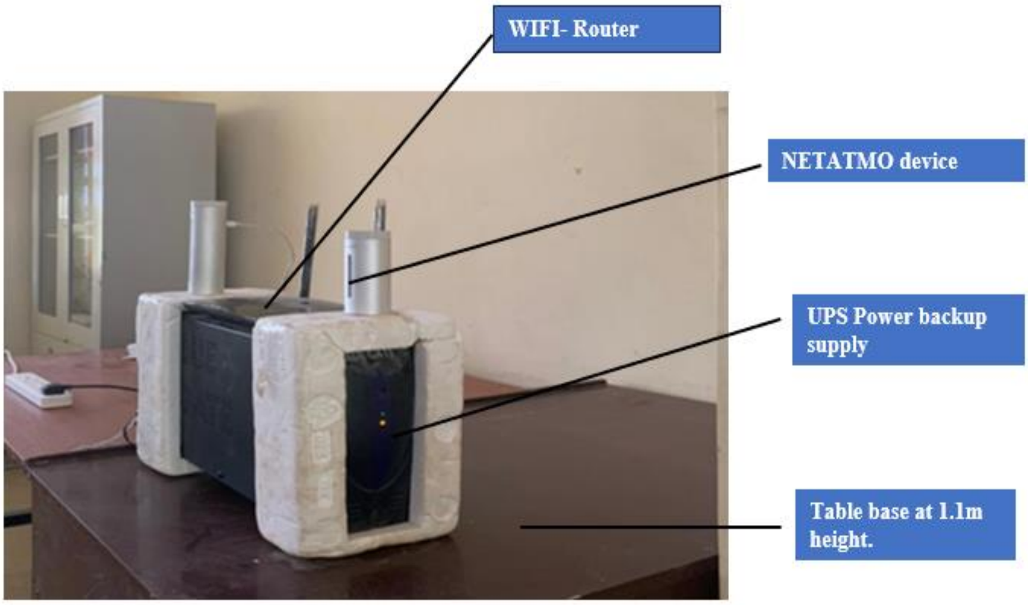


Figure 4-1 The indoor setup and stationing of NETATMO smart device

Table 4.1 Technical Specifications of Netatmo Smart Weather Device

Smart Home Weather Station's technical specifications

Sensor	Range	Accuracy
Temperature (indoor)	0 - 50°C	±0.3°C
Temperature (outdoor)	-40 - 65°C	±0.3°C
Humidity (indoor/outdoor)	0 - 100%	±3%
CO_2	0 - 5000 ppm	±50ppm, ±5%
Sound level	35 - 120 dB	-
Wind speed	0 - 45 m/s	0.5 m/s
Wind direction	-	5°C

4.1.2 *HOBO-Onset Data Logger*

To track changes in interior lighting and room occupancy, HOBO® UX90-006 Data Logger was installed, illustrated in Table 4.2, to measure the parameters. The device was fastened at the top windowsill to capture both natural and artificial light sources.

Table 4.2 Technical Specifications of HOBO UX90-006 Logger for Occupancy and Light

Occupancy Sensor	
Detection Range	maximum 12 m
Detection Performance	-20° to 70°C
Light Sensor	
Light Threshold	> 65 lux
Logger	
Time Accuracy	±1 minute per month at 25°C

The device has a 128 KB memory model (UX90-006) with 84,650 measures, and an enhanced 512 KB memory version is offered. The device's main benefits are it can accurately measure room occupancy up to 12 meters away, has ON and OFF thresholds auto calibrated to assure accurate readings, has an LCD screen that shows signal strength and allows for optimum logger placement. Highly recommended light pipe accessory, which may be used with HOBO-ware and HOBO-ware Pro software for logger setup, graphing, and analysis, is linked to eliminating ambient light's influence to provide the most accurate results.

4.1.3 Experimental Setup, Calibration and Results.

The environmental conditions of the case study building were monitored over a period extending for one cooling season to assess its thermal comfort. The monitoring activity was carried out using tools for objective instrumentation of the indoor studio space to measure relative thermal indices, following guidelines as discussed in many research by Guevara et al. (2021), Mishra and Loomans, (2018), Kooi et al. (2018), Tahsildoost and Zomorodian, (2015). These state research showed when subjective occupant preferences were compared with the result from measurement to achieve transitional thermal responses a comprehensive view that provide solution to the problem can be achieved.

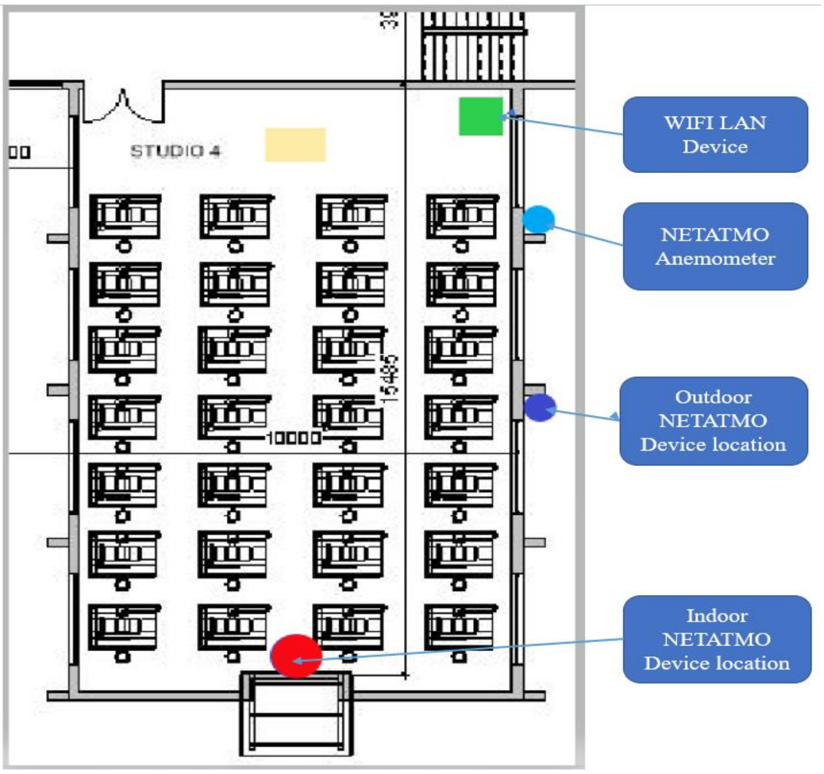


Figure 4-2 The indoor stationing of data logging devices is inside and outside the studio.

The studio halls measure 10.0m in length, 6.0m in width, and 3.5m in height with a rectangular shape (Figure 4-2). It has six external walls with windows facing east and west, without any shading device to protect against direct solar radiation. However, the furniture arrangement within the hall was strategically designed to favour the viewing angles of students towards the north in each of the four studio halls. To ensure accurate measurements of thermal parameters, the NETATMO device was placed at a strategic location deep inside the room, behind the last row, where desired values can be observed or estimated to occur. This location was chosen to avoid errors caused by air drought and direct solar radiation impact on logging devices. The NETATMO and HOBO-light and occupancy devices were positioned at a height of 1.0-1.1m in the studio, considering the different activity levels of occupants, such as sitting or standing during lectures, studio work, or presentations, according to the ASHRAE 55 guide. The NETATMO Anemometer was logged outside to measure air velocity and directions, and it has the same technical specification of sensor accuracy as the other main component.

To accurately measure thermal indices in the studio environment, NETATMO loggers were utilized for a full year and HOBO loggers for a week to monitor periods of high student activity and academic engagement. The NETATMO loggers track air temperature, mean radiant temperature, humidity, CO_2, and noise levels every hour. However, the server only records data every 30 minutes, with daily minimums, weekly averages, and monthly means. HOBO loggers were calibrated to record lighting (on and off) and occupancy every 30 minutes, with output in percentages and hours. The selection criteria for all loggers were efficiency, accuracy, and durability against extreme weather conditions. For detailed instrument specifications, see Tables 4.1 and Figure 4-2.

Lighting measurement in the 400-level studio was achieved using the HOBO-Onset device, Table 4.2, to achieve lighting comfort indoors and the concentration of students in the studio at certain times of the day. The device can record 420-680 lux during the summer if window orientation impacts daylight admittance. The operates on-and-off light/ occupancy and output in hours or percentage (%). Recommended studio Lighting efficiency for teaching and learning range of 300-500 Lux illuminance at desk height in classrooms, auditorium, and lecture theatres according to CIBSE LG5 and BS EN12464-1, (F. C. Park, 2015).

There are equal numbers of installed facilities that run on electricity in the 4-studios and the 2-workshops; this equipment supplies lighting and power, which include energy-saving fluorescent and incandescent bulbs/lamps and mechanical ventilation facilities such as fans and ACs. Other devices include a projector and a public addressing system, which consume energy. Table 4.3 presents the breakdown of power requirements and percentages for different types of electrical equipment in the studio building. Notably, the air conditioning system constitutes approximately 72.46% of the total installed power, with fans accounting for 5.80%. The electrical lighting load is around 4.83%, attributed to using energy-efficient fluorescent light bulbs that deliver adequate illumination while consuming minimal electricity. Furthermore, other electrical loads in the building are relatively low, owing to the high energy efficiency of the equipment and because the building was occupied.

Table 4.3 Energy consumption of the facilities in 400L Studio.

S/n	Name of Appliance	Unit (N) Watt (W)	Quantity	Total Watt (W*N)	% Energy
1	Bulbs Energy Saver (B)	40	12	480	3.86
2	Bulbs Energy Saver (Sl)	20	6	120	0.97
3	Air-condition units (AC)	1500	6	9000	72.46
4	Ceiling Fans	60	12	720	5.80
5	Public addressing system	100	1	100	0.81
6	Laptops	70	25	1750	14.09
7	Projector unit	250	1	250	2.01
	Total	2040	63	12420	100

i. Air Temperature

Figure 4-3 displays the recorded minimum and maximum indoor temperature indices during the overheated period in April 2020. The highest recorded temperatures were on the 6th and 17th of the month, at 44.7°C and 43.0°C, respectively. The lowest readings were recorded on the 8th to 11th days of the month, with a temperature range of 32.4°C to 35.6°C. The daily difference between indoor and outdoor temperatures ranged from 2°C to 10°C, typical of hot and dry climates. This temperature fluctuation may also impact other comfort parameters. According to Bidassey-Manilal et al., (2016), school classrooms should have a minimum indoor temperature of 18°C and a recommended maximum of 26°C. Temperatures above 26°C are considered unacceptable. It is also advised to keep classroom temperatures below 32°C during the day and 26°C at night. Figure 4-4 indicate minimum highest and lowest readings recorded on the 9 -11th days of the month with temperature of 32.4ºC to 35.6ºC, both at night and due to the windows opening outdoor to the surrounding landscape. There was a slight temperature increase for indoor spaces of about 1 to 2.5ºC due to the interaction between heat built-up infiltration and the inflow of hot air to interiors, especially regarding the absence of landscaping elements, window shading elements and the window opening in the east and west orientations.

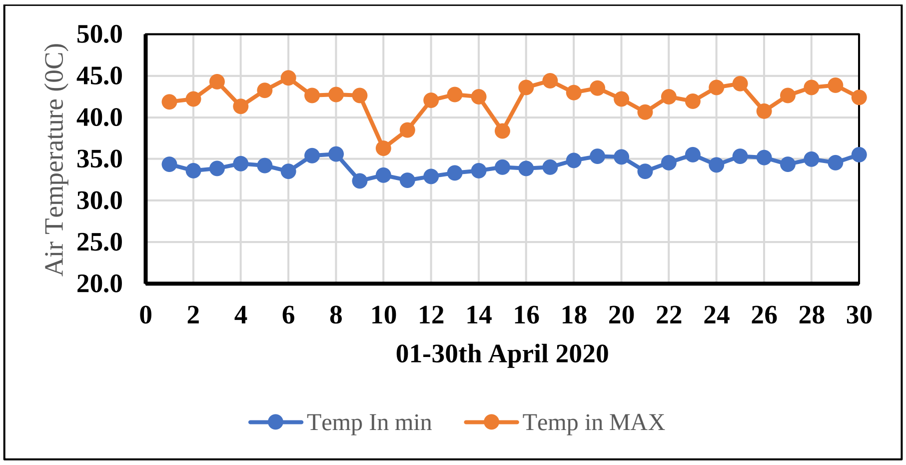


Figure 4-3 Indoor air temperature (minimum and maximum); month of April.

Occupants' operatives of switching on air conditioning sets and fans to cool the interiors are other factors. The indoor-to-outdoor (minimum and maximum) daily temperature difference was a significant characteristic of the temperature of hot/dry climates.

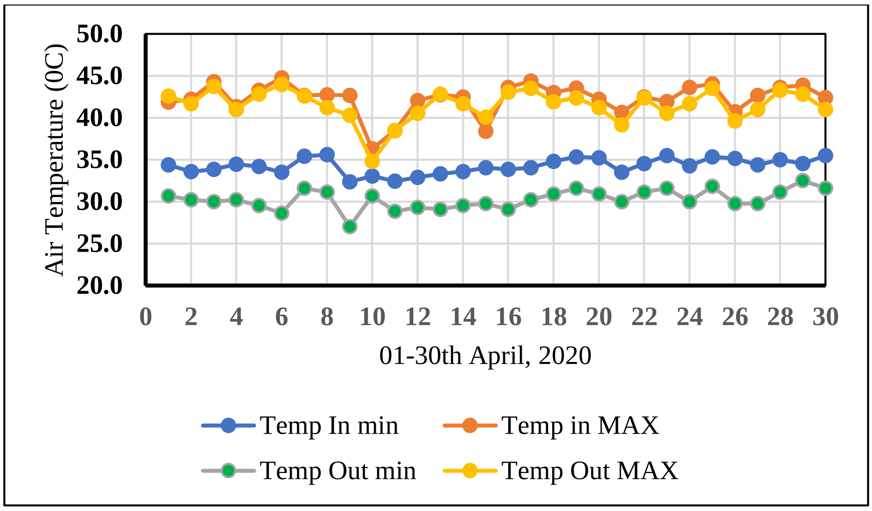


Figure 4-4 Combined Indoor and outdoor temperatures (minimum and maximum) in April.

ii. Relative Humidity

Figure 4-5 shows the large varying relative humidity values, with 49% on April 11th and a drop of 13% on April 17th, indicating dryness. The indoor environment is modified by the outdoor temperature in terms of humidity.

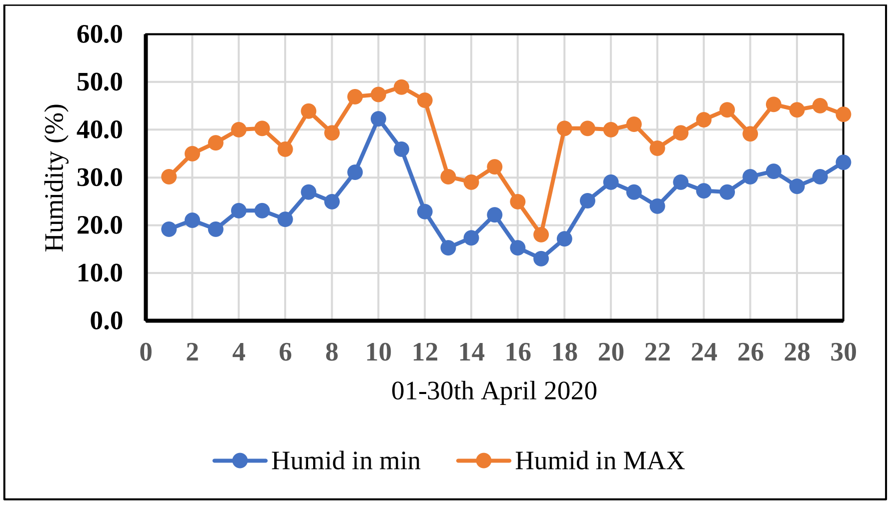


Figure 4-5 Indoor relative humidity levels (minimum and maximum) in April.

The lowest humidity values were obtained on the 16th and 17th, among the hottest and driest days of the month, with 15% minimum and 28% (Figure 4-6). Value indices change in humidity outside the building. The measurement of indoor humidity was modified by the temperature of the outdoor value indices in readings due to the change in humidity outside the studio, which increased from 20 to 30%, but was higher due to the daily temperature rise. Reflecting on this indicates the air is hotter, with minimum moisture content.

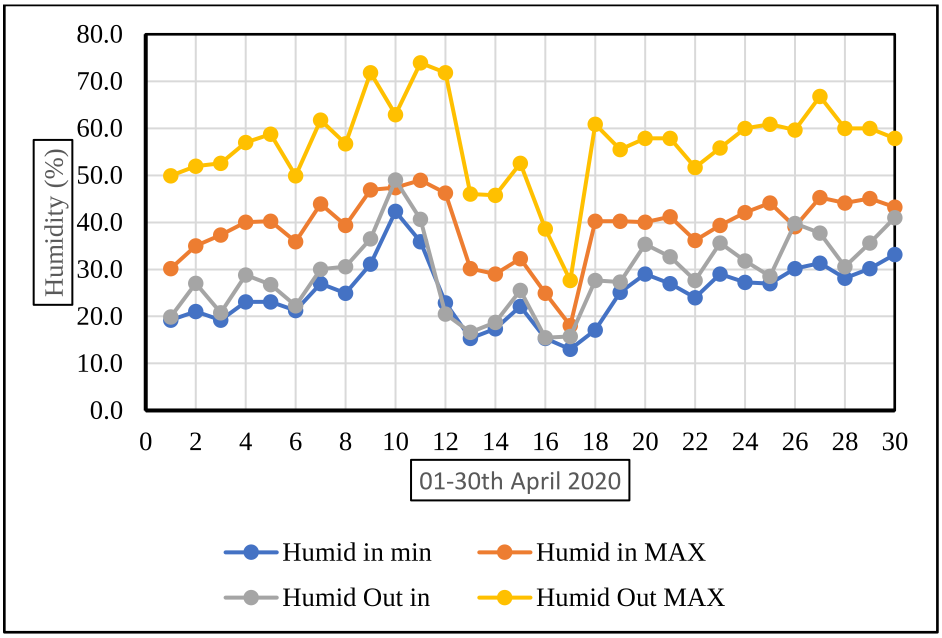


Figure 4-6 Combined indoor and outdoor relative humidity levels (minimum and maximum) in April.

iii. Carbon dioxide (CO_2) and Air quality (IAQ)

Defining minimum indoor ventilation for IAQ standards and thermal comfort based on CO_2 requirements is challenging due to factors like building type, climate, gender, and human activities (ASHRAE-62, 2022; Stumm, 2022; Persily, 2015). Figure 4-7 illustrates that the lowest indoor CO_2 concentration is 1880 ppm, on 21st April in the 400-level studio, while the maximum recorded CO_2 concentration in the studio during the month of April was 1960 ppm. This value is slightly higher than 1920ppm recorded for the hottest day (10^{th} April). Overheating in April exceeded the threshold by 90%. The high CO_2 concentration observed in this study exceeds 1500 ppm prescribed by ASHRAE-62 and ASHRAE-55 standards. According to Vilčeková et al., (2017), Carbon dioxide concentration in classrooms should not exceed 1000 ppm, but 600-800ppm is considered a mild concentration for ensuring indoor air quality, health, and wellbeing of occupants. It is observed that the CO_2 levels consistently remain high, thus, occupant operative and hybrid-ventilation are suggested as a solution to reduce overheated indoors.

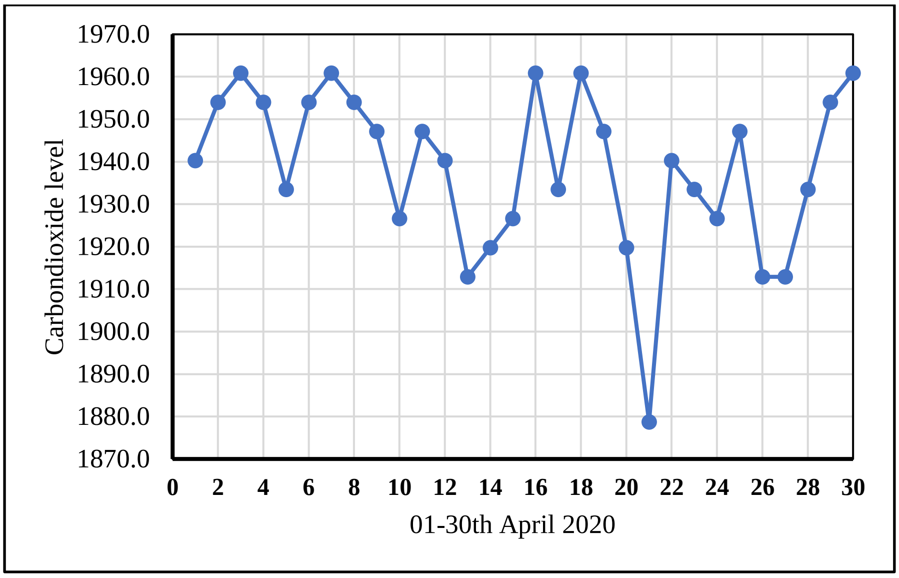


Figure 4-7 ***Indoor Carbon dioxide (C02) levels (measured) in 400L Studio in April.***

iv. Air velocity

The outdoor air velocity measured in the month indicates days 9, 17, and 26 have the highest recorded values of wind velocity of more than 10 m/s at maximum levels with lower values at 0.2-1m/s. The impact of wind makes the average wind speed range from 0.2 m/s in the morning to 11.1 m/s during the afternoon, as shown in Figure 4-8. The wind speed has a significant influence on the thermal sensation of students during the days recorded and is consistent with past earlier survey questions asked. Significant also is because of wind pressure and high temperature difference this will causes an increase air speed without temperature reduction and due to absence of vegetation.

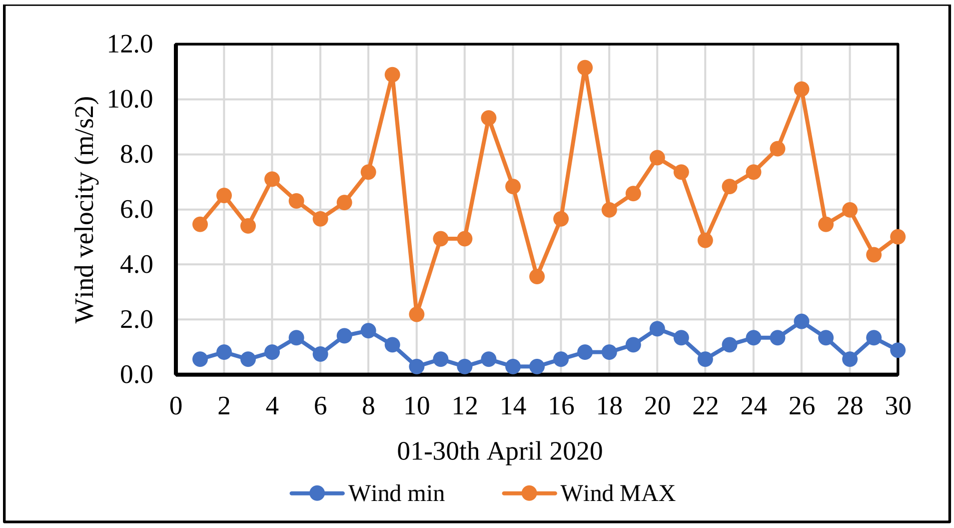


Figure 4-8 Outdoor Wind velocity (minimum and maximum) in April.

v. *Noise level*

Figure 4-9 shows that the noise level in the 400-level studio recorded for the entire month of April was under 40 db. Although this was the highest-level recorded value, this level is normal and healthy for teaching. The noise level in the studio is lower than the ASHRAE-55, (2017), minimum standard (56.5-68.5 dB) specifically for educational purposes. A higher noise level (62-96 dB) would require building insulation.

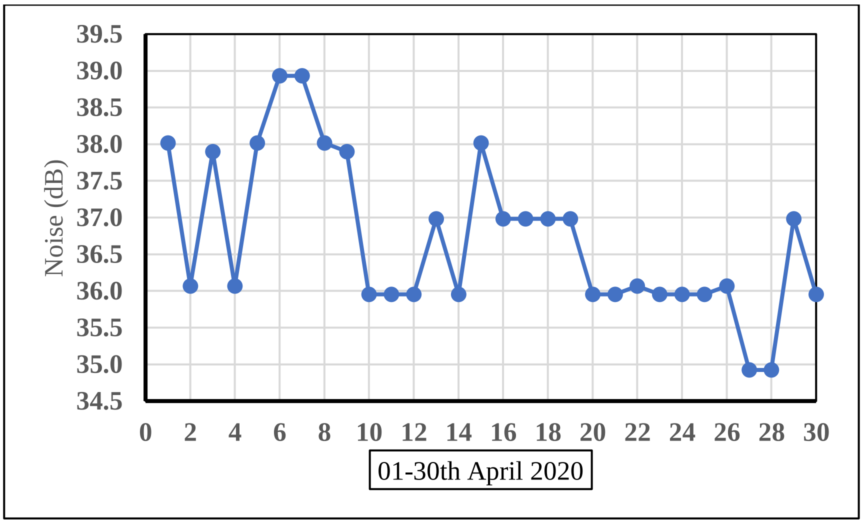


Figure 4-9 Indoor Noise (measured) in 400L Studio in April.

vi. Occupancy and Lighting

On weekdays, the HOBO Lighting and Occupancy device shows that the studio is occupied at a rate of 65-100% in the morning, between 8:00hrs and 13:00hrs. The lighting is turned off at 9:00hrs and remains off until 17:00hrs when it is needed for studio work. Figure 4-10A shows that fluorescent and energy-saving bulbs provide full artificial lighting in the studios from 17:00hrs until daybreak, with approximately 50% occupancy. During the weekend days, the studio is fully occupied at a rate of 100% between 8:00hrs-10:00 and 14:00-16:30hrs for assigned lectures. In comparison, 50% of occupancy is observed at night with full artificial light, as shown in Figure 4-10B. To provide comfort, mechanical cooling, and ventilation are fully powered and operational from 12:00 (noon) to 17:00hrs, while night studio work requires artificial lighting for 16 hours or more daily.

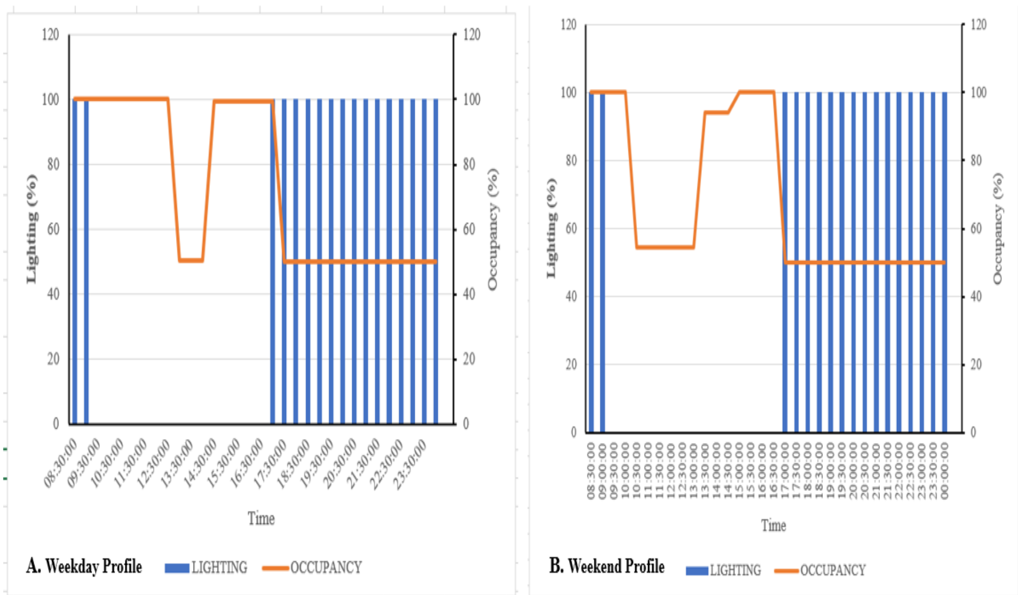


Figure 4-10 Lighting and occupancy weekday (A) and weekend profile (B).

4.1.4 Result Discussions

Efficient data logging devices are important for error detection during measurement processes. NETATMO and HOBO-Onset offer useful features like sensor calibration and device connectivity. The ASHRAE-55 standard recommends an accuracy error within 5% and a precision error within 10% for a good measurement system ASHRAE-55, (2017). The NETATMO device meets this standard. Environmental weather data is crucial for analysing results. There was a slight temperature difference of 2°C when comparing outdoor radiant temperature measured by NETATMO and NASA/POWER CERES/MERRA2 global system data. Humidity readings showed a slight discrepancy in overall monthly measurement; therefore, limited day assessments are required in buildings for a full understanding of the environmental situation, as recommended in Abdallah, (2022) research. Minimum IEQ requires an optimisation plan to reduce CO_2 levels and maintain a comfortable temperature. A quality indoor atmosphere is important for studio users to provide healthy, comfortable, and increased productivity. Shaded windows increase natural ventilation during provision inside classes which can be achieved through efficient use of sensors to measure mechanical ventilation and CO_2, as reflected in (ASHRAE-62, 2022). The thermal comfort analysis shows that air temperature exceeded global system data from NASA, exceeding the thermal comfort limit ($T_{comfort}$). Monthly mean radiant temperature data from NASA and monthly mean indoor temperature were used to calculate the upper and lower thermal comfort limits based on (Nicol & Brian, 2013). Figures 3.21 illustrate the calculation.

One way to assess overheating in educational buildings is by using a fixed temperature criterion, specifically focusing on the standard effective temperature (SET) point having minimum and maximum limits and values for the temperature inside the building and counting the number of exceedance hours (Ji et al., 2019, Dai and Jiang, 2021). A set point of 28°C was recommended by the adaptive thermal comfort approach as outlined by Nicol and Brian (2013); Nicol and Spires, (2013). In addition, TM52 guidelines and 101BB, (2018). This highlights that effective indoor thermal comfort temperatures are influenced by the outdoor running mean temperature, which is specific to European climates.

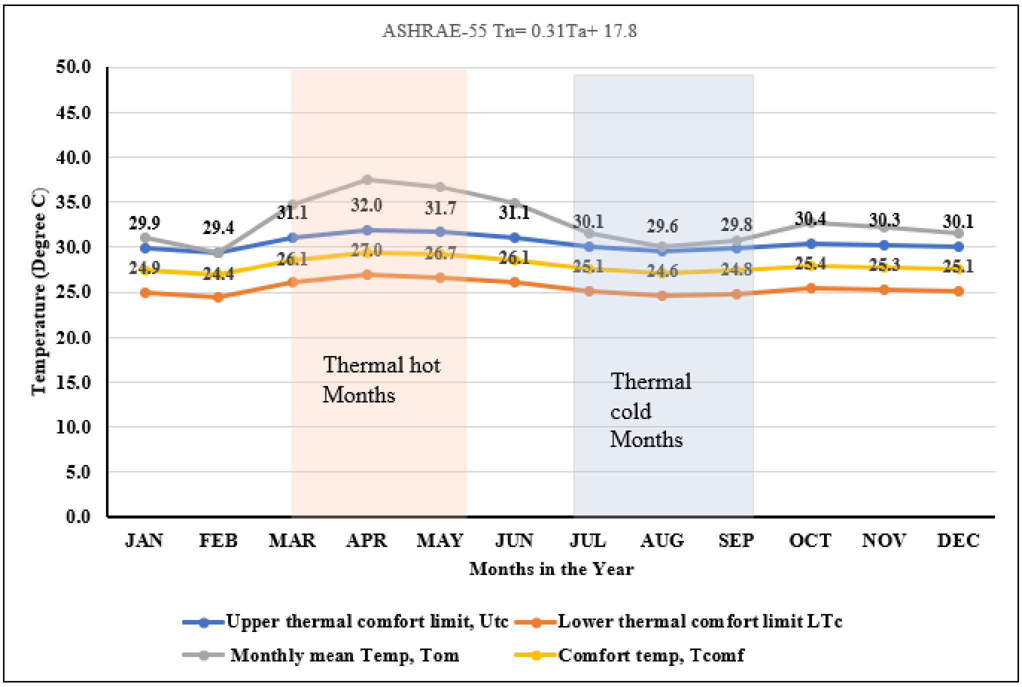


Figure 4-11 Calculated Monthly Thermal comfort limits across the Year using Nicole's Equation.

The studio structure was mechanically ventilated therefore, the ANSI/ASHRAE Standard-55 (ASHRAE, 2017) specified that the area was anticipated to be comfortable for many occupants, including maximum temperatures and relative humidity levels. With the same monthly mean of the external temperature, a range of operative temperatures was created comparable to operative temperatures in naturally ventilated structures. The two ranges were between which the approval of the occupant was 80% to 90%. The ASHRAE standard's adaptive comfort is given by (4-1).

$$T_{comf} = 0.31T_{om} + 17.8 \tag{4-1}$$

where T_{comf} = the comfort temperature and Tom is the monthly mean outdoor temperature, the outdoor monthly mean temperature = (T_{om}) this will be the running mean and monthly mean temperatures. The calculated lower thermal comfort limit temperature illustrated in Figure 4-11for the hottest month of April was 27.0ºC lower and the upper limit 32.0°C; within these limits is the standard effective temperature (SET), state conditions when the environment and the skin (body) temperature a neutral. However, the operative temperature set points lower and upper limits in January's coldest month were calculated as 24.6ºC and

29.6°C. The measurement process provides input parameters on calculating and improving thermal comfort conditions in buildings that enhance users' activities and building utility/functions as suggested by (IPCC, 2022; Aghniaey and Lawrence, 2018; Lomas; Giridharan, 2012).

The essential of setting thermal comfort limits were recommended by the findings from field research of comfort and energy efficiency, lamenting that existing buildings and newly designed, constructed, and retrofitting should be timely evaluated to address the most important source of discomfort, its variables in achieving thermal comfort requirements, by classifying the occupants' personal control and adaptive options (Arens et al., 2020; Wang et al., 2021).

4.2 Post-Occupancy Assessment (Interviews & Questionnaire)

The occupants of the Architectural Studio complex were engaged in a subjective process to indicate their preferential vote (PMV and PPD) regarding thermal comfort, building and environment, and appreciation of the facility during the survey. This section presents the results of the interviews, questionnaires, and survey methodology from the presentations and analysis. An initial report on measurement in section 3.3, discussed earlier, provided insight into this section regarding provisional standards and guidelines and is relative to this analysis.

The User Evaluation Process commenced with a survey conducted for managers and occupants of the studio building. This survey aimed to gather feedback from occupants on their perception, acceptance, or satisfaction with the thermal comfort of the building, its performance and operations, productivity levels, and health and well-being, and managers on how to maintain the facilities, through two methods: structured interviews and questionnaires. Data from these observations was collected and compared with measured values.

The first part of the survey was the structured interviews conducted with the university's Director of Physical Planning. The interview questions were sent to his email before the main interview was conducted in his office in June 2021, after the physical survey of the building. The interview covered various aspects, including the approval of the contract, the construction stages and processes of operation, building usage, maintenance, energy efficiency, and the impact of environmental factors on the building.

The second part of the survey was the questionnaire, designed using the ASHRAE 55 methodology and applied through an online Google form. The questionnaire was distributed to academic staff and students and aimed to assess their thermal comfort perception, health and well-being, building performance experiences, and user satisfaction with the building's structure and aesthetics. The data obtained from the questionnaire will be used as observed data and compared with measured data for analysis.

4.2.1 Interview Structure

After a thorough building survey, extensive interviews were conducted with the Director and senior staff of the Physical Planning Directorate (PP&D) of the University. The PP&D department supervises and maintains the entire physical infrastructure. An interview was conducted to gain additional insights that complement the occupants' questionnaire responses. The interview questions, which were sent via email to the Director and three other senior staff members, focused on the following topics:

i. Building construction and occupancy
ii. Building usage operations
iii. Building systems and operations, including energy efficiency
iv. Building maintenance for user comfort in the indoor learning environment.

The interview data will be used in a framework for building maintenance and retrofitting processes, and it will also provide information for the parametric process. The following interview questions were tagged and answered under the headings below.

i. *Building Construction Stages and Occupation*

The construction of the building followed the project template of the Federal Ministry of Education. It was funded by the Tertiary Education Tax Fund (TET Fund), which is responsible for the development of higher educational institutions in Nigeria. The project was supervised by the Department of Physical Planning of the University, and it took 12 months to complete, starting from February 18, 2018, with the Studio building being occupied on February 6, 2019. The Director of Physical Planning and Development stated that the Studio complex was the projects' first phase been the first building to be constructed on the faculty layout site. There were four structures in total, which had unique shapes and heights but similar utility functions. These structures included the Faculty Administrative building, a 250-capacity Theatre complex, the Architectural Studio complex, and the classroom complex. They were considered as the first phase of the contract, and the remaining buildings would be awarded for phase-II development. The Architecture Studio complex was fully occupied during the interview, and other structures were nearing completion. The building has six studios, three on each of the two levels. The building is a new dedicated learning space for Architecture design students.

ii. *Building Usage and Operation*

When question about the usage and operation of the building was asked during the interview; explanation was given that: 'The Studio complex, which has six studios, became fully operational in December 2019. The building has three entrances and stair halls. The four major studios can hold up to 45 students each, while the central studios can hold up to 25 students. The ground floor studio is for computer work, while the first floor is for model-making. All presentations are to be held in the studios, which can lead to overcrowding and discomfort. Mechanical devices are readily installed in all studios to improve ventilation and comfort.

iii. Building System and Operations

Regarding building system, energy supply, and operations: The building has switches and sockets that control lighting fixtures and ventilation equipment, such as fans and air conditioners that rely on electricity. Each studio hall has 8 large windows on the east and west sides and 6 fixed windows on the 2 central studio openings. The window-to-wall ratio is 40% on the east and west sides, and the windows are manually operable systems for natural air and ventilation. These large windows also allow direct solar insolation from 9:00 to 17:00 hours of the day, which could cause severe heat impact in summer. All studios have electronic communication devices for teaching aids and plug-in audio and visual communication outlets. These devices consume energy and release a small amount of heat that can affect human comfort.

Occupants reported uncontrolled natural lighting arising from large east-oriented windows. The energy-saving lamps and bulbs provide sufficient artificial lighting in all the studios. Although Studios should have an adequate supply of natural light from the windows and artificial lighting system because students work throughout the day and night, glare could be a problem. However, artificial lighting, communication gadgets, and mechanical ventilation consume electricity. During an interview, the Director of Physical Planning lamented that the monthly electricity consumption rate could not be ascertained due to the non-provision of bills by the Power holding company. Instead of monthly bills, a lump sum bill of consumption for all the buildings in the university's permanent site campus is presented for monthly payment to the electricity supply company.

iv. Building Maintenance

During the interview, the Director of Physical Planning explained that the new studio complex must meet the "Defect Liability Period" requirement. This provision, included in the contract document, allows for a six-month observation period, which includes the rainy season, to identify any defects in the completed building. If any defects are found, the contractor must fix them before receiving the retention money, which is 5% of the total contract sum. This maintenance period is also outlined in the relevant sections of the Nigeria Building Code document (NNBC, 2006).

The Physical Planning Division's Technical Staff are responsible for managing all university buildings, except for specific services and facilities contracted out to external facilities management companies. If occupants notice any defects in the building, they must report them to PP&D for maintenance and repairs. Routine maintenance of facilities is scheduled every six years, as discussed during the interview.

4.2.2 The Questionnaire Structure

This section discusses the occupant evaluation process and describes a subjective methodology that involves an online questionnaire. The questionnaire follows the ANSI/ASHRAE Standard-55 of the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) standard guidelines. The guideline is used in research to achieve the minimum provision of occupant comfort and in building performance designs, energy efficiency, and productivity. Over time, this standard has been modified to address current issues in the built environment (Arens et al., 2020; ASHRAE handbook, 2021).

The questionnaire was given to the academic staff and students of the environmental science faculty at the Federal University Birnin Kebbi. It consisted of 34 questions, divided into 6 sections. There were 21 questions related to thermal comfort, 13 personal questions, and questions assessing the occupants' health/well-being and indoor environmental quality. The survey began with an email asking the faculty Dean for informed consent. The questionnaire's first section provided details about the survey's focus, the survey area, the environment, and the time allotted for completion. It also included legal aspects like the University of Nottingham privacy notice and the General Data Protection Regulation (GDPR) guidelines that participants must agree to before proceeding. The other sections included questions about thermal comfort parameters, occupants' control and activities, and building form appreciation. You can refer to APPENDIX IIIA and IVA Questionnaire Model for more details. The questionnaire was given to the academic staff and students of the environmental science faculty at the Federal University Birnin Kebbi. It consisted of 34 questions, divided into 6 sections. There were 21 questions related to thermal comfort, 13 personal questions, and questions assessing the occupants' health/well-being and indoor environmental quality. The survey began with an email asking the faculty Dean for informed consent.

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Section 2 requires participants to agree to take part in the survey.

Section 3 asks personal questions about the participants, including gender, age, education level, status, identity, building name, and the date and time of the survey. The survey also asks about the floor level of the building, studio sitting position, and clothing worn during the survey. Respondents are asked to indicate their desk areas and how they respond to indoor thermal conditions.

Section 4 asks participants about their thermal comfort satisfaction based on specific parameters, such as air temperature, radiant temperature, relative humidity, and air velocity. They are asked to vote based on their subjective feelings and by predictive mean vote (PMV). The questionnaire addresses aspects relevant to comfort, including indoor/outdoor perception of temperature, humidity, air quality, and light as in (Yatim et al., 2011).

Section 5 asks participants about the personal adjustments they make to reduce the impact of interior overheating, including adjustments to building fittings/fixtures, operable windows and doors, and mechanical/electrical gadgets.

In **Section 6**, participants are asked about their satisfaction with the building's form, shape, and aesthetic as established in (Serghides et al., 2015)They are also asked about their perceptions of passive design principles and the utilization of building materials to improve indoor thermal comfort. The questionnaire contains 21 questions set under specific question tags.

Table 4.4 Questionnaire structure

S/No,	Question (variable) Levels	Question number
1.	Comfort Sensation Perception Votes	1,2,3,4,5,8,9, and 10
2.	Other Comfort parameters votes: Daylighting, Artificial lighting, Visual and Noise	6,7,15, 19, 20 and 21
3.	Adjustment and control	11, 12, 13,14, and 16
4.	Health and Wellbeing	10 and 18

4.2.3 Questionnaire Features

The online questionnaires were administered based on the PMV and PPD 7-point scale of ASHRAE-55 guidelines. The questionnaires are designed to gather responses from both students and lecturers regarding factors such as temperature, humidity, CO_2, and noise levels in studios and classroom environments. Building measurements will be used to validate these responses. The purpose of the questionnaire is to assess environmental features that may impact the comfort of those occupying the indoor space. These factors can lead to overheating and the need for mechanical devices, which can result in unsustainable energy consumption. It is important to understand that a building's energy consumption is directly linked to the thermal and visual comfort of its occupants. By asking about their perceptions and behaviours within the building, we can investigate and correlate the data. The research will focus on assessing thermal satisfaction and heat sensation votes on a scale with the following descriptions: during summer (high solar radiation) and winter (specifically, December-February) in studios and classroom environments.

(-3 to +3). Description**:** -3 = Cold, -2 = Cool, -1 = Slightly Cool, 0 = Neutral, +1 = Slightly Warm, + 2 = Warm, +3 = Hot.

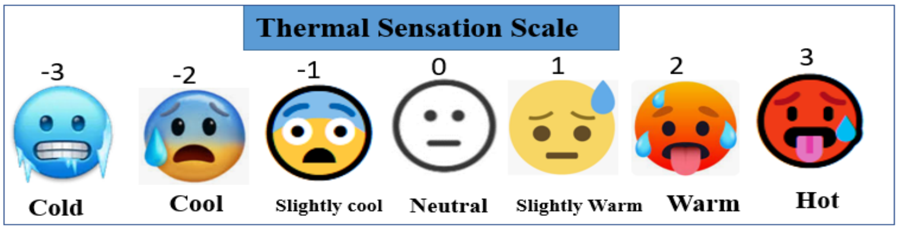

Figure 4-12 The Thermal Sensation Scale

Figure 4-12 illustrates the thermal sensation with a 7-point description of (-3 to +3). Where (ASHRAE -1 to -3) are numbers 1-3 and 4= 0 Neutral, and (ASHRAE +1 to +3) represents 5 to 7.

Figure 4-13 illustrates the description of the comfort scale: 1. Very uncomfortable, 2. Uncomfortable, 3. Slightly uncomfortable, 4. Neutral, 5. Slightly comfortable, 6. Comfortable, and 7. Very comfortable.

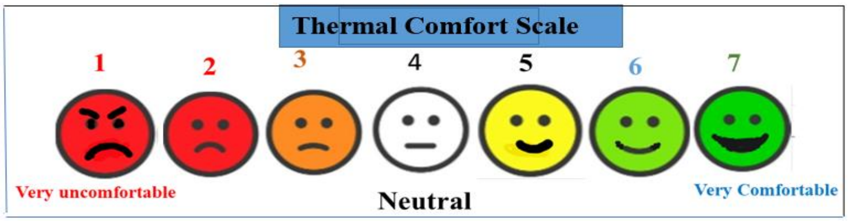

Figure 4-13 The Thermal Comfort Scale

Figure 4-14 describes the thermal satisfaction scale: 1. Very dissatisfied, 2. Dissatisfied, 3. Slightly dissatisfied, 4. Neutral, 5. Slightly satisfied, 6. Satisfied, and 7. Very satisfied.

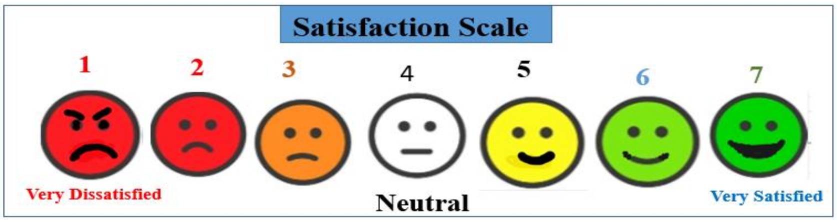

Figure 4-14 The Thermal Sensation Scale.

Other PMV descriptive scales used in the questionnaire are as follows:

Description: 1. Never, 2. Rarely, 3. Occasionally, 4. Neutral, 5. Slightly regularly, 6. Regularly and 7. Very regularly.

Description: 1. Greatly interfere, 2. interferes, 3. Slightly interfere, 4. Neutral, 5. Slightly enhanced, 6. Enhanced, and 7. Greatly enhanced.

Description: Yes and No.

4.2.4 Questionnaire Application and Process

The feedback from occupants, responses to the questionnaire, on their comfort perception levels and experiences with overheating in indoor environments was gathered. The survey specifically targeted the months of March to June when temperatures tend to rise and cause discomfort, heat stress, and reduced productivity. The survey guidelines and invitations were sent to the occupants of the studio building, a case study in the faculty of environmental sciences at a university (see APPENDIX I and APPENDIX II). The purpose, nature (online), application process and title were highlighted in the invitation to participate sent to undergraduate students and academic staff. In total, 62 people participated in the online questionnaire, and the survey responses were arranged by population in Table 4.4 and Figure 4-15. Participants who agreed to participate were emailed a link to complete the survey during a designated class session. Information about the survey and how to participate was also provided during studio work hours.

Table 4.5 Class Population and Respondents

S/No	Class/Level	Population	Respondents	Percentage %
1	100	37	13	21
2	200	28	5	8
3	300	25	6	10
4	400	45	25	40
5	Lecturers	15	13	21
	TOTAL	150	62	100

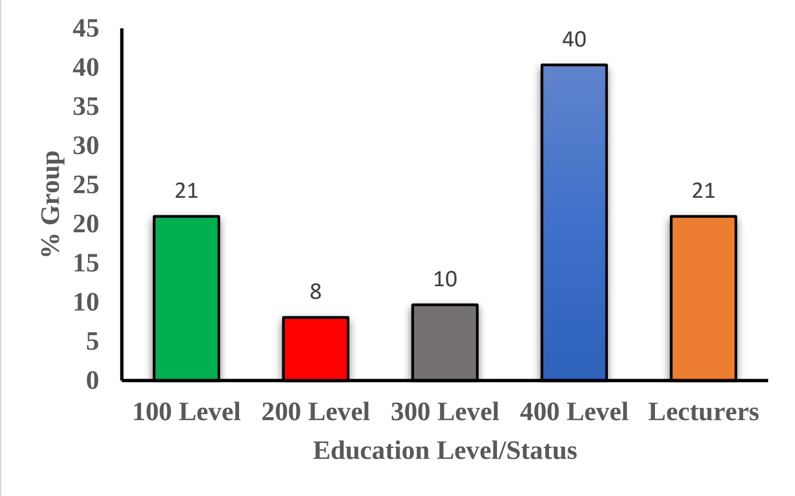

Figure 4-15 Class Population and Respondents.

To minimize disruption to occupants' academic schedules, surveys were conducted after lecture periods and during morning or early afternoon breaks. Late afternoon sessions were also an option, but not too late to interfere with design studio work. All responses were recorded as the survey was conducted online, with participants able to withdraw at any time. No incentives were given for participation, and participants were only thanked for their voluntary input. Responses were kept anonymous, and a 15-minute time frame was given to complete the survey. Participants were provided with internet WIFI connectivity to answer questions on the spot after a brief explanation of the survey process. This streamlined the process and saved on expenses, as the building had limited internet connectivity during the survey.

4.2.5 Overview of Statistical Package for the Social Sciences (SPSS)

The responses of the occupants to the online questionnaire were analysed using the Statistical Package for the Social Sciences (SPSS) program. IBM developed this tool in 1968 for statistical data analysis. According to Keleş et al. (2021), SPSS when applied to predictive model datasets, it is regarded as scoring the data. IBM® SPSS® Statistics includes procedures for building predictive models such as regression, clustering, tree, and neural network models. Once a model is built, its specifications can be saved in a file containing all the necessary information to reconstruct it. This file generates predictive scores in other datasets. SPSS procedures produce a model XML file; some produce a compressed file archive (.zip files) with Microsoft Excel output. SPSS also measures the reliability of survey questions. It is a powerful application that can perform almost any statistical analysis and data processing in a user-friendly Windows environment. According to Aldrich & Rodríguez (2009), it can calculate mean values (*fx*) using the number of valid observations for the variables 'N', the total number of valid non-missing values in each group. The mean value of the dependent variable is also determined for each level of investigation of the independent variable. The application of SPSS also derives the frequency distributions and correlation of statistically significant value (p-value), a probability value that expresses whether the data are under the null hypothesis, which is to be rejected or accepted if the value of $p < 0.05$ or -0.05, considering negative (-) and positive (+) scales in Kruskal-Wallis and Wilcoxon signed-rank tests. The analyses of regression values with a correlation coefficient (r) depend on the factors of investigation, as in research (Paliaga et al., 2013; Dias Pereira et al., 2014; Serghides et al. 2015).

The SPSS statistical tool offers interphases for the analysis of the questionnaires. Encoding, filtering, charts, graphs, and Table that were created in both Excel tools and these forms of analysis were used by Gupta et al. (2020); and Mezhennaya and Pugachev (2019) in similar research to complement the use of both single and two applications. The SPSS tool is used to analyze different types of data measurements. It summarizes data in categories, such as gender or marital status. Qualitative data is represented using numeric codes to categorize information, for example, 0 for unsatisfied and 1 for satisfied. There are two main types of categorical data: nominal and ordinal. Ordinal data includes key rankings, such as service satisfaction levels from very satisfied to very dissatisfied but does not have a measurable numeric value. Categorical data has an order of categories and a numeric value representing the distance between them. This type of data is measured on a scale interval or ratio scale and is also known as quantitative or continuous data (Serghides et al. 2015).

When analysing data, categorical data can be used to determine the number or percentage of cases in each category. The mode identifies the category with the highest number of cases. For ordinal data, the median (the value at which half of the cases fall above and below) can also be a helpful summary measure if there are many categories. The Frequencies procedure generates frequency tables to display the number and percentage of cases for each observed value of a variable. Additionally, this tool can be used for T-tests, One-Way analysis of variance, Bivariate Correlations, Linear regression, Ordinal Regression, Factor Analysis, Multiple Response Analysis, and Clusters Analysis (Warton, 2022).

4.2.6 Kruskal-Wallis H Rank test: One way ANOVA

The Kruskal-Wallis H test, also known as the "one-way ANOVA on ranks," is a nonparametric test used to determine if there are significant differences between two or more groups of an independent variable on a continuous or ordinal dependent variable. This test is used when the assumptions of one-way ANOVA are not met and for analysing independent random samples with three or more populations. It is an extension of the Mann-Whitney U-test, which allows the comparison of more than two independent groups. However, it is important to note that the Kruskal-Wallis H test cannot specify which specific groups of independent variables are significantly different from each other but can indicate at least two groups are different. This test may be limited in providing multiple statistical results for many groups, making it essential to determine which groups differ from each other, especially when there are three, four, five or more groups in the study (Randolph & Myers, 2013).

The Kruskal-Walli’s test is also used to compare the average ranks of different population samples. This method is used when there are more than three groups, and the data is not normally distributed. The test compares the medians of each group to determine if there is a significant difference between them. It is like one-way ANOVA and is used when normality is not met. The probability value

(p) is typically greater than 0.05, indicating weak dominance power of the test (Ganthier & Hawley, 2015, Cleophas & Zwinderman, 2016). The Kruskal Wallis test is also like Wilcoxon's Rank Sum test and T-test; therefore, comparing the sum of ranks applies to the data. The Wilcoxon sign test uses ranked or ordinal data is an alternative to the dependent samples t-test when the assumptions are false. The test statistic is calculated with the equations (4.3 and 4.4).

$$\mathrm{K} = \frac{12}{\mathrm{N(N+1)}} \sum_{i=1}^{k} \cdot \frac{R_i^2}{n_i} - 3(N+1) \qquad (4.3).$$

K = number of groups used for comparison

N = total size of the sample

n*i* = *i*-th sample size of the groups

R*i* = total of the ranks related to *i*-th group. (Cleophas & Zwinderman, 2016).

The above formula is valid only for a group of samples with a minimum of five elements and no estimated population barriers. When the population distribution has no assumption, sample groups are independent, with random data selection in every group having a minimal ordinal. The correction factor, *C*, is denoted by equation (3.4).

$$C = 1 - \frac{\sum_{j=1}^{g} t_j^3 - t_j}{N^3 - N} \qquad (4.4).$$

where g is the number of tied groups, and *tj* is the number of tied data in the *jth* group. This is for the large *N* data set.

4.2.7 Application of Kruskal-Wallis H Rank Test

Applying the Kruskal Wallis to the questionnaire process was focused on consideration of all the environmental factors, while the studio geometry sizes and orientations remained constant; the test for this assessment was to know whether the overheating experienced by the respondents (ranks) in studios impacts the thermal comfort of occupants. Thermal comfort perception of individuals differs from person to person, affecting whether they are in the same environment (uniform) or otherwise (Nicole, 2013).

4.2.8 Analysis of Kruskal-Wallis H Rank Test

The uniform environment of four studios was analysed to determine the level of discomfort experienced by occupants due to indoor overheating. The Kruskal Wallis tool was used to find the statistically significant difference between the median scores of the occupants. The results are presented in two tables, one showing the ranks/groups and means distributions, and the other displaying the outcomes. The process and approach was similar in Asif et al., (2022), Ezennia, (2022) and Afolabi et al., (2017) research, which was guided by Kruskal Wallace and Wilcoxon's level of significance, ranked test analysis in achieving the desired objectives (Cleophas and Zwinderman, 2016).

4.3 Application of Thermal Comfort Perception Questionnaire

The survey was conducted during the summer season, which spans from March to July in Birnin Kebbi. It was conducted on April 12th between 12:00 noon and 2:00 pm, when students were fully engaged in their studies. The outdoor temperature was at its peak at 39-41◦C, with a relative humidity of 65% under clear sky conditions. Both students and staff in studios ranging from 100 Level to 400 Levels were surveyed. The questionnaire and results tables can be found in APPENDIX IIIA and IIIB of this report. There was a need to gather responses using a questionnaire on thermal comfort and analyse them using descriptive statistics. The study engaged students and staff in investigating various activities in the building, such as lecturing, attending lectures, and designing in the studios. The culture attached to the building is for students to stay in the studios throughout the day and work on their designs at night after morning classes. The use of gadgets such as computers was prevalent among staff and students. The metabolic rate of individuals was found to be average for both seasons, with an average value of 1.3 met. Students and staff wore lightweight clothing in the hot season and traditional attire in the winter. The indoor summer clothing in winter was 1.0 *clo* and 0.5 *clo* in summer.

4.3.1 Questionnaire Results and Discussion

Below are the important findings from an online survey conducted among the staff and students of the Architectural Studio complex in a Nigerian university. The survey had 62 respondents, including males (87%) and females (13%) aged between 18 and 67. The survey results were presented in figures and charts, highlighting the correlations between the users' responses. The survey focused on the participant's knowledge of the building, their perception of its visual appeal, and most importantly, their comfort level in the indoor environment, considering Nigeria's hot, dry climatic zone. Statistical data related to these factors can be found in Figure 4-16. (See APPENDIX IIIB of Arch. Studio Questionnaire Results; Tables).

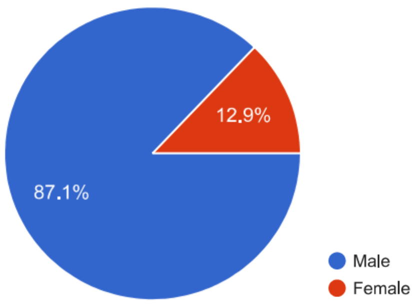

Figure 4-16 General statistics of the respondents, Male and Female.

i. Indoor Temperature

The occupants' overall air temperature perception votes inside the studios vary across the scale. Votes in this analysis were presented under two cumulative scales (uncomfortable and comfortable) across the four studios, although the 7-point PMV scale (-3 to +3) was used.

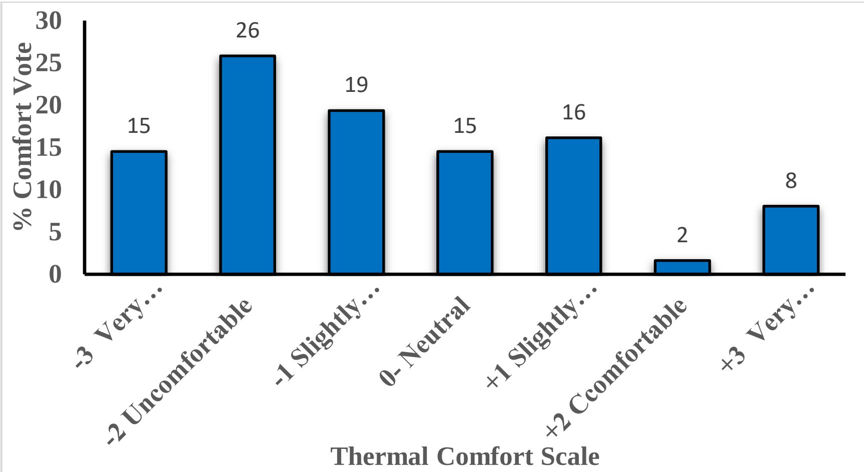

Figure 4-17 Comfort vote of air temperature in interior spaces of studios

Figure 4-17 results indicate that about 59.7% of respondents who voted were uncomfortable with the indoor temperature in the studios, while 25.8% were comfortable. Neutral responses of 14.5% were recorded. According to Singh et al. (2011)The occupants inside a building can adapt to different temperature variations in different climatic zones and seasons of the same climatic zone. These adaptive coefficients also consider the local climate and sociocultural setup, saying further that different climatic zones must be assessed in temperature and other thermal elements throughout the year. It is ideal for calculating occupants' predictive mean votes (PMV) for more accurate values.

ii. Humidity

Of the total humidity votes, 39% are uncomfortable with a mean of 2.14. On the positive side of the scale, 29% of the occupant are comfortable with a mean value of 3.44, while 24% of respondents feel neutral; thus, neither belonging to either the positive or negative side of the scale, as illustrated in Figure 4-18 According to Shahzad et al. (2018), the neutral scale does not guarantee thermal comfort. Thus, neutral votes are insignificant.

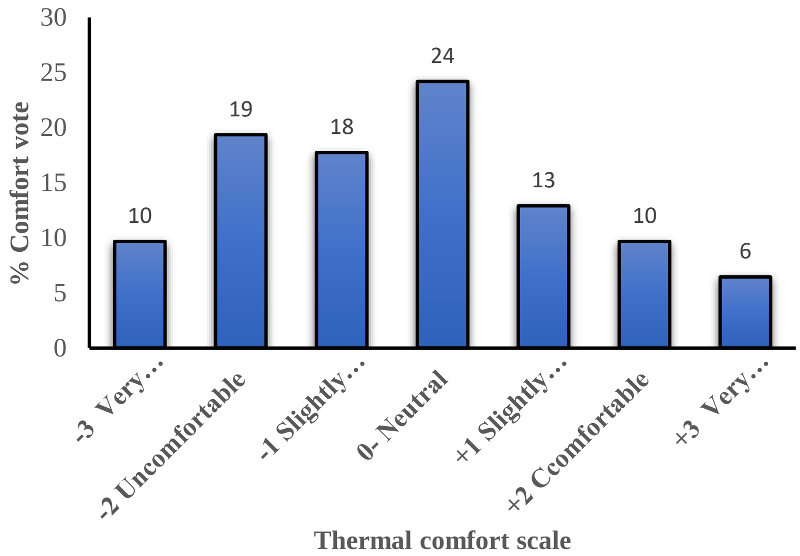

Figure 4-18 Comfort vote of Humidity in Interior Space.

Further the analysis indicates that most occupants (Staff and students) seem to be uncomfortable with the Humidity in studio spaces at the time of the survey, this was because occupants in all studios and at both floor levels can switch on the mechanical devices at any suitable time to regulate the indoor environment.

iii. Air Quality and Carbon-dioxide level

Air quality is critical in achieving comfort in interiors. Figure 4-19 shows the frequency distribution of the 7 air characteristic levels in the indoor studio space. Air quality perception in the studios is associated with Carbon dioxide (CO_2) levels. Above 1500 parts per million (ppm) was considered a high health risk to the occupants of the building (ASHRAE-55, 2017). Sufficient air movement in interior space reduces the risk of high CO_2 build-up and filters the indoor air thus reducing health-related risks. The votes in Figure 4.19 indicate that 22% of occupants are comfortable, 14% considered the air fresh and 11%, odourless on the positive index, while the remaining 53% of votes were associated with risks of air pollution.

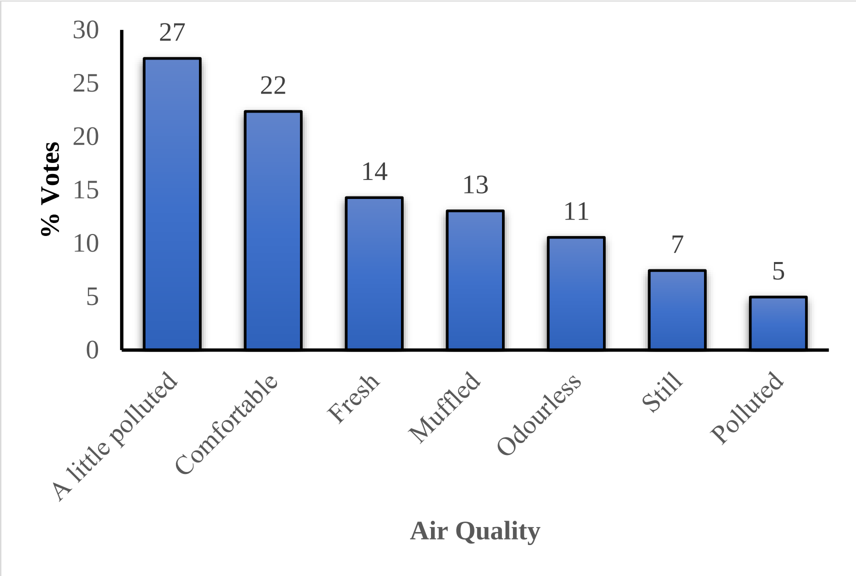

Figure 4-19 Perception of Occupants on Indoor Air Quality

iv. Ventilation and Air Buoyancy

Thermal satisfaction with the fresh air was voted for on a 7-point scale in Figure 4-20. The air buoyancy chart shows that an average of 25% of the occupants across all the studios were dissatisfied with the air velocity in the studio; about 18% confirm they are neutral, while only 5% indicated they are very satisfied. that of satisfaction votes for fresh air in studios with the mean value and the percentage distribution. Further analysis reveals that students at the ground floor level complain of high velocity of dusty particles of air going into the studios in the winter season; this is also the period of cold and dusty breeze called *(harmattan)*season, associated with poor visibility; this weather phenomenon compelled students to close windows during the day. The absence of natural landscape elements makes the interiors grossly short of fresh air supply and serves as natural dust particle filters.

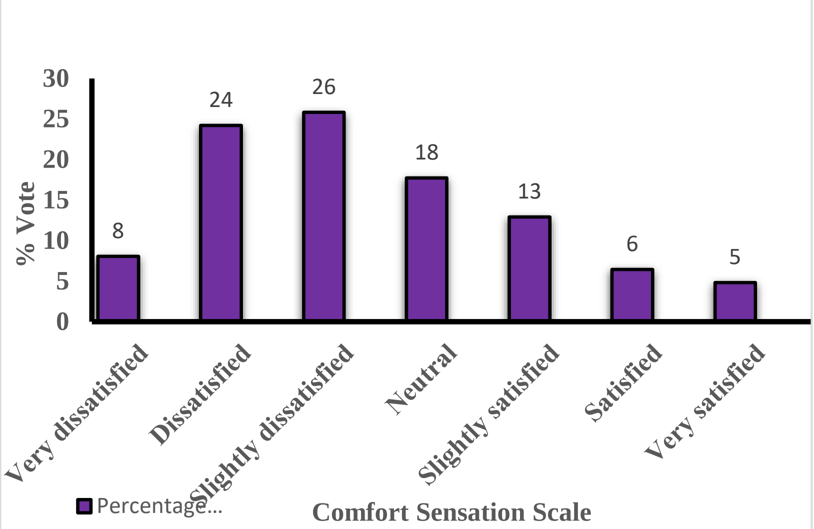

Figure 4-20 Thermal Satisfaction with Fresh Air in Studio

v. *Thermal Sensation in summer months*

Figures 4-21 Illustrates how the occupant predictions in terms of heat perception in relation with thermal indicators. The questionnaire asked studio users about their thermal sensation in hot summer season where 96% of occupants indicate they feel hot and only 4% feels cold. This has fully fallen within recommended (90%) satisfaction range.

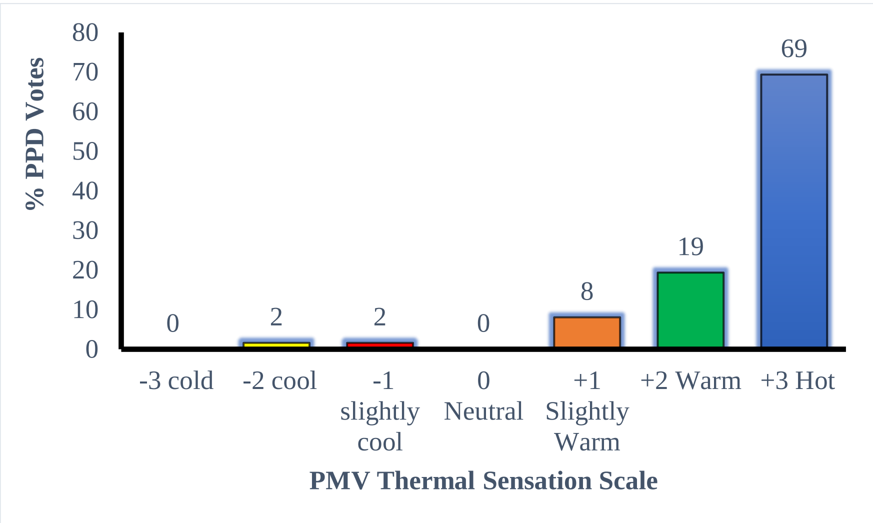

Figure 4-21 Consideration of thermal sensation in the hot season.

vi. Health and well-being

When asked if they experienced any symptoms due to overheating perception in the studio, the respondents had varied responses. 18% of them reported feeling fatigued when exposed to daytime heat in the hot season, 18% felt restless, 7% experienced dizziness, 12% felt sleepy, and only 2% felt tired most of the time. However, 37% reported sweating (as shown in Figure 4-22). These experiences became more intense during solar overheating between 2 pm and 5 pm, resulting in a period of 6 hours of heatwave discomfort, which could be problematic.

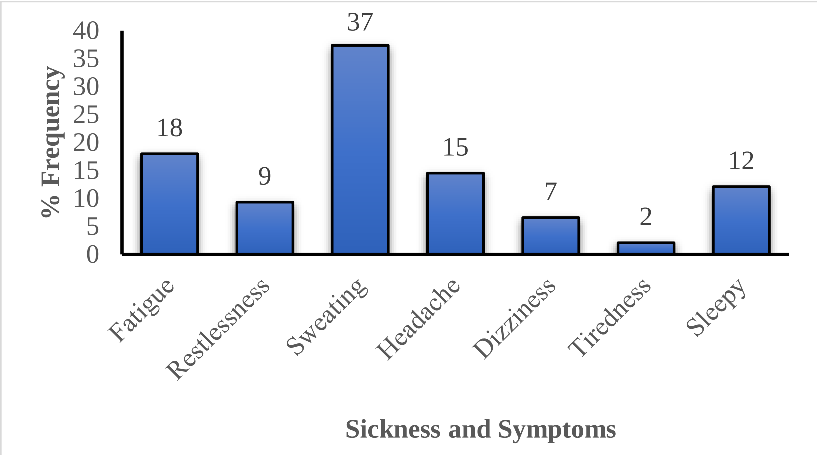

Figure 4-22 Ailments associated with Heat perception

vii. Clothing and Insulation

The survey asked about the comfort level of clothing worn by occupants. According to the responses from male participants, 42% wear traditional clothing, 21% wear short sleeves and trousers, 11% wear track suits, and 10% wear long sleeves Figure 4-23. It should be noted that traditional clothing is usually thick, not light, but many still choose to wear it during the summer months. The clothing worn is determined by the local climate and sociocultural norms of the region. The distribution of clothing worn by staff and students is uniform and does not vary significantly. Further analysis is needed to determine the insulation ratings of the clothing based on the PMVs and to compare the differences in what men and women wear.

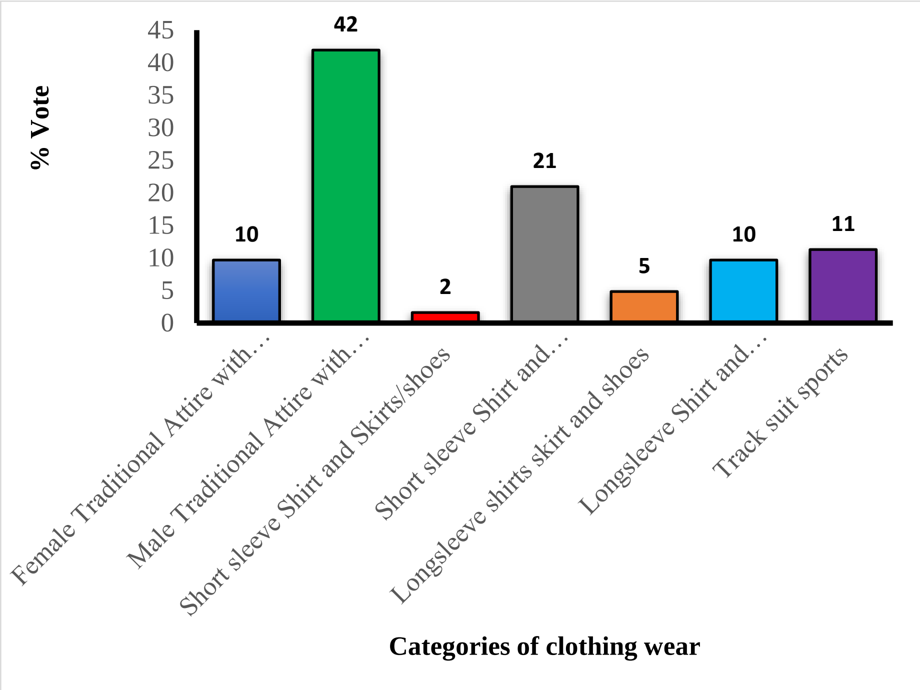

Figure 4-23 Clothing Wear by Survey Respondents

Based on research by Soebarto et al., (2019) and De Dear et al., (2015), when recording clothing indices in classroom settings, it's important to consider the clo value for both sexes. Women tend to have higher values and are more likely to wear warmer clothing than men. The study also looked at garment insulation ratings and how well PMV can differentiate between the two. Adjusting clothing levels is crucial to maintain comfort in different temperatures. The thermal comfort survey found that 42% of traditional clothing for males is worn by males, and 21% voted for wearing short sleeves, with females mostly wearing traditional garments and long sleeves at 10% votes. Clothing values range from 0.5 clo in summer to 1.5 clo in winter. Interestingly, students adapt to a unique type of clothing that reflects the slight changes in seasons, but the clothing levels in one season are not significantly different from the other.

viii. User Operative and Control

The survey asked about controlling ACs, fans, and windows for optimal indoor comfort. Nearly all respondents (99%) adjusted devices based on their needs (Figure 4-24). Differences existed between lecture classrooms and studios, with the latter having larger furniture and longer occupancy (24 hours) all day. Excessive electricity consumption was a concern. Students clustered around devices during high-activity periods, but settings could be adjusted. All appliances were used throughout the day, except during winter when they were less frequently used. They were fully utilized during the hot season.

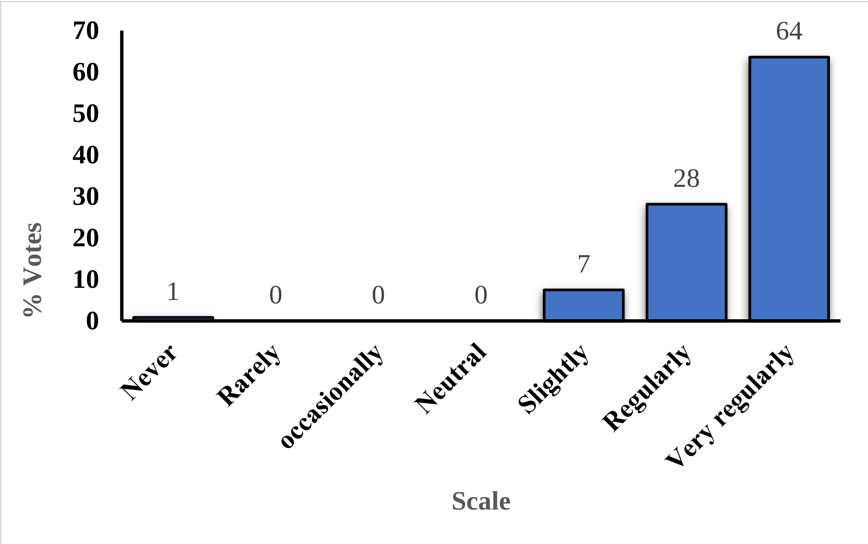

Figure 4-24 Frequent use of control operable and mechanical gadgets

ix. Productivity in the Indoor Environment

The occupants of the studio were asked to rate how the building impacts their productivity, particularly how their work productivity is affected by the indoor environmental conditions for comfort. They provided their responses on a scale of 1 to 7 (-3 to +3) concerning interference and enhancement. The results showed that 84% of the occupants experienced an improvement in their productivity, while 16% reported interference due to the indoor environmental conditions. Figure 4-25 provides a visual representation of these findings. Although the acceptability of PMV was not achieved by 90%, 80% of the occupants gave a positive rating, which is considered reasonable.

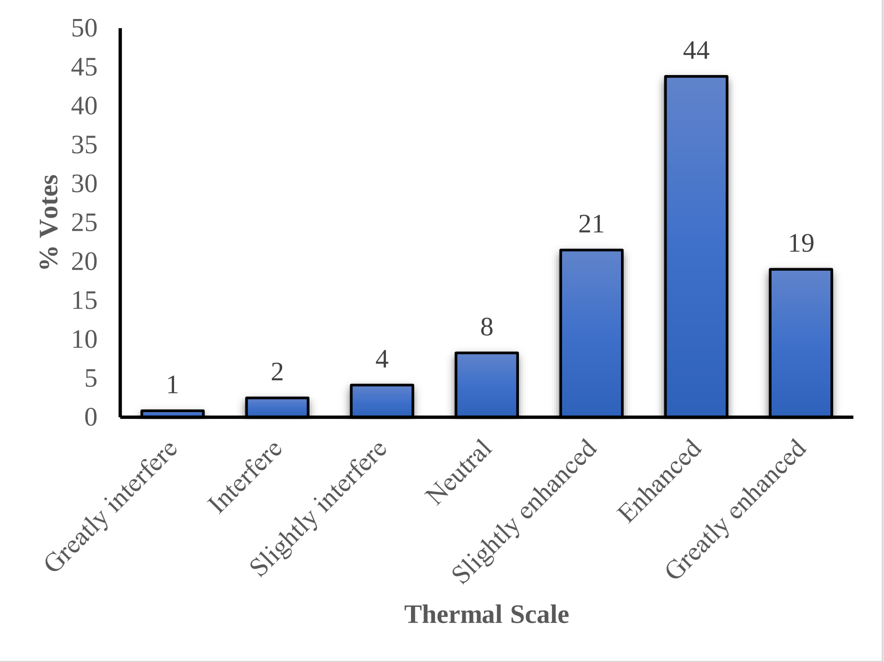

Figure 4-25 Productivity and work Performance.

x. *Building Form Aesthetic Quality and Environment*

Occupants in the survey were asked about their satisfaction with building form and aesthetics; results showed 61% satisfaction and 26% dissatisfaction votes. 18%, 24% and 19% are on a positive satisfaction scale, with 13% undecided (Figure 4-26). Students and lecturers were asked about this to guide future building upgrades and maintenance. Engaging with occupants is important for personal feedback of their perception and feelings in space and the environment, according to (Zomorodian et al. 2016, Nico et al. 2015).

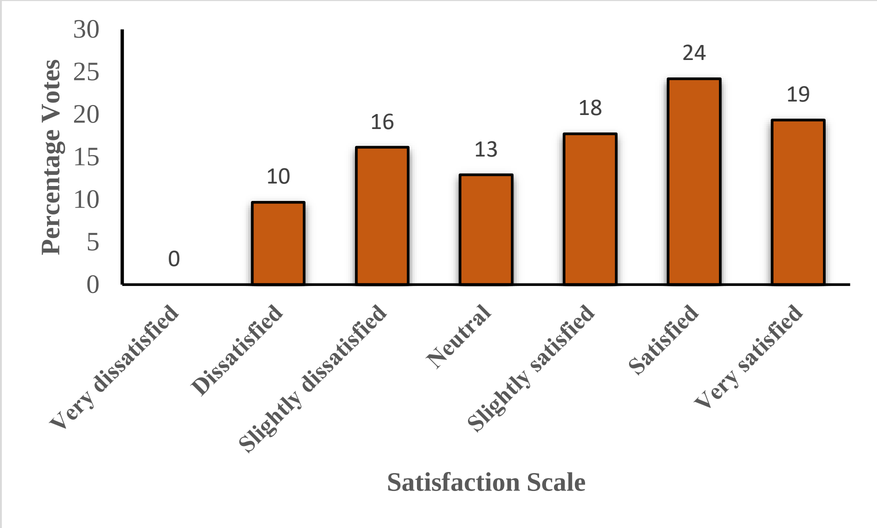

Figure 4-26 Building Form, Aesthetic quality, and environmental appeal.

4.3.2 SPSS Analysis of Questionnaire Results and Discussions.

The thermal comfort perception of occupants in the Architectural studio complex is analysed using SPSS tool, based on research questions: Overheating sensations in seasons, comfort perception under the parameters, including temperature, humidity, air quality (IEQ), lighting and Noise levels across the seasons. Tested using the Kruskal Wallis null hypothesis to ascertain the significance level in each case. When null is rejected, the resulting statement would be uphold based on the distinction of probability p-value of 5%, and z-value which dictates how the average rank of each group can be compared to the average rank of all observations that would justify the research questions on statical perspective. (See APPENDIX VA Questionnaire SPSS analysis; Tables).

Question 1: How similar (or close) are the distributions of thermal sensations in the hot season and thermal conditions in the winter/ rainy season? The Wilcoxon Signed Ranks Test is used because the level measurement of the categories is ordinal. The test result from the population (N=62) with Mean Rank; (26.00 and 27.53) proved that the null was rejected at 5% significance level. Thus, there was a significant difference between the thermal sensations during the two seasons, this was because z-value= -6.200 at provability of 0.000. Example Table 4.5, illustrates.

Table 4.6 Wilcoxon Signed Ranks Test

		Ranks N	Mean Rank	Sum of Ranks
How would you consider the thermal sensation in the hot season? - How would you describe the thermal conditions in winter/rainy season?	Negative Ranks	1	26.00	26.00
	Positive Ranks	53	27.53	1459.00
	Ties	8		
	Total	62		
Z	-6.200			
p-value	.000			

Null Hypothesis: There is no significant difference in the distributions during hot and winter/rainy seasons, or the thermal sensations of the two seasons are equal.

Conclusion: The null was rejected at a 5% significance level; thus, there was no significant difference between the sensations during the two seasons.

Question 2: Are there significant differences in the distribution of the measured thermal comfort parameters (i.e., temperature, humidity, satisfaction with the level of fresh air, comfortability of the lighting in the lecture room workspace and the satisfaction of the noise level in the indoor space) during the hot season? The appropriate test here is the Krustal Wallis Test because the level measurement of the categories is ordinal.

Null hypothesis: No significant differences exist in the measured thermal comfort parameters distribution during the hot season.

Conclusion: Among all measured thermal comfort parameters, only temperature in the workspace was significant at a 5% significance level during the hot season. There was a difference in the distribution level of this parameter during the season.

Question 3: Are there significant differences in the distribution of the measured thermal comfort parameters (i.e., temperature, humidity, satisfaction with the level of fresh air, comfortability of the lighting in the lecture room workspace, and the satisfaction of the noise level in the indoor space) during winter/rainy season? The appropriate test here is the Krustal Wallis Test because the level measurement of the categories is ordinal.

Null Hypothesis: There are no significant differences in the distribution of the measured thermal comfort parameters during the winter/rainy season.

Conclusion*:* Among all measured thermal comfort parameters, only the feeling of relative humidity in the workspace was significant at a 5% significance level during the hot season. The distribution level of this parameter was different during the winter/rainy season.

Question 4: Is there a difference in the distribution of sitting arrangements for students in the lecture studio, considering the floor level? The appropriate test here is Kruskal Wallis. The categories' level measurement is **ordinal.**

Null Hypothesis: Considering the floor level, there is no significant difference in the distribution of sitting arrangements for students in the chosen lecture studio.

Conclusion*:* Failed to reject the null and concluded that there was no difference in the distribution of sitting arrangements for students in the chosen lecture studios.

Question 5: Is there a time in a day when environmental thermal comfort is the most a problem?

Null Hypothesis: Thermal comfort is the same across the time of day. The appropriate test here is Krystal Wallis. The level of measurement for the categories is **ordinal.**

Conclusion: The null hypothesis was rejected for the period between 2 p.m. and 5 p.m. because thermal comfort is not the same across time and periods of the day.

4.3.3 Summary of Measurements and Survey

Experimental monitoring of the case study building using NETATMO data logger and associated sensors. This allowed the quantification of indoor environmental quality (IEQ), thermal comfort, and occupants' adaptation to the heat beyond the IPCC minimum standard and recommended temperature of 26°C for educational buildings. The findings highlight a higher minimum and maximum SET for April (the hottest month) as 27.0ºC lower and upper limit 32.0°C, and January's coldest was calculated as 24.6ºC and 29.6°C. The comfort temperature of 29.5°C for occupants in the studio building for operations is applicable to the hot/dry climatic zone of Nigeria.

Based on the analysis, it was found that there was a notable difference in how occupants perceived discomfort and heat stress between the two seasons. During the hot season, occupants felt high temperatures the most in studios compared to other thermal comfort parameters. Meanwhile, dryness was most noticeable during winter. Additionally, occupants' discomfort levels varied throughout the day and over time. Analysis of thermal comfort is crucial in studio environments to prevent overheating. A questionnaire and interview method helped understand occupants' perceptions and adjust the indoor environment for efficiency. Adapting the space can address each person's unique thermal perception. Objective and subjective views were gathered, revealing complaints about high temperatures and low humidity. Improving the building fabric can enhance performance, provide thermal comfort, and improve indoor air quality from passive cooling.

CHAPTER FIVE

5. POST-OCCUPANCY THERMAL COMFORT EVALUATION: CASE OF CLASSROOM COMPLEX, FEDERAL UNIVERSITY BIRNIN KEBBI, NIGERIA

5.1 Introduction

This chapter evaluates a classroom complex through subjective and objective processes. Interviews, questionnaires, surveys, and instrumentation were used to gather information about indoor environmental quality, user thermal comfort, and other environmental factors. Data loggers were used to collect thermal comfort indices to ensure that the indoor environmental quality meets the minimum standards for the well-being of building occupants.

5.2 Instrumentation and Measurement of Environmental Data

Experiments were conducted for two seasons, hot and cold. Months of March to May, with April 2021 described as the hot season, when the mean outdoor air temperature was approximately 40^{o} C, and December 2021, for the cold season, when the mean outdoor air temperature was 26°C. Experimental measurements were conducted for the selected classrooms 'B' on the ground floor. It recorded the highest occupancy of 48 students; it is mostly occupied and utilized for lectures. which makes it possible to be chosen and data logged at strategic points with the NETATMO Smart home weather measuring device and HOBO UX90-006 Data Logger for Occupancy and Light was installed to monitor room and indoor light changes to identify occupancy patterns and determine energy usage and potential savings. The process covers the 2-seasons. Thermal comfort variables (i.e., air temperature, mean radiant temperature, air velocity, relative humidity, CO2 emissions, lighting, and Noise level) were monitored for the overheating period, guided by the ASHRAE 55- Standard document. The same data logging processes in the studio building (Case study A) were followed as explained in (Shi et al., 2022; Nico et al., 2015).

The 6-classroom are equipped with electrical lighting and cooling devices such as lighting bulbs (energy savers), ceiling-mounted fans, split air-conditioner public addressing systems, and projector units that consume enormous electrical energy. Table 5.1 shows the unit, total, and percentage energy consumption of electrical appliances in the classroom 'B.' The total estimated energy consumption is 14760W for all the facilities, with air conditioning units having 12000W, indicating its enormous energy consumption by (ACs) followed by 1050 consumption if all 15 students connect their laptops to electricity. The energy-saving capacity of bulbs has the lowest consumption of 640W.

Table 5.1 Energy consumption of the facilities in Classroom 'B'.

S/no	Name of Appliance	Unit (N) Watt (W)	Quantity	Total Watt (W*N)	% Energy
1	Energy Saver Bulbs (B)	40	16	640	4.34
2	Air-condition units (AC)	1500	8	12000	81.30
3	Ceiling Fans	60	12	720	4.88
4	Public addressing system	100	1	100	0.68
5	Laptops	70	15	1050	7.11
6	Projector unit	250	1	250	1.69
	Total	2020	53	14760	100

5.2.1 The Experimental Set-up and Calibration

The experimental set-up starts with instrument calibration in Classroom 'B' and subsequent device logging at strategic points. Considering that the classrooms are the same in size, equipment, and planning, the instruments were installed per the ASHRAE 55 (2017) standard guidelines. NETATMO indoor and outdoor device locations are shown in the architectural plan of the classroom in Figure

5-1(a); instruments are kept away from noticeable heat sources set at a 1.0-1.1 m height, as indicated in Figure 5.1(b). The HOBO (occupancy and light) logger was clipped to the window side, where the light source can be recorded.

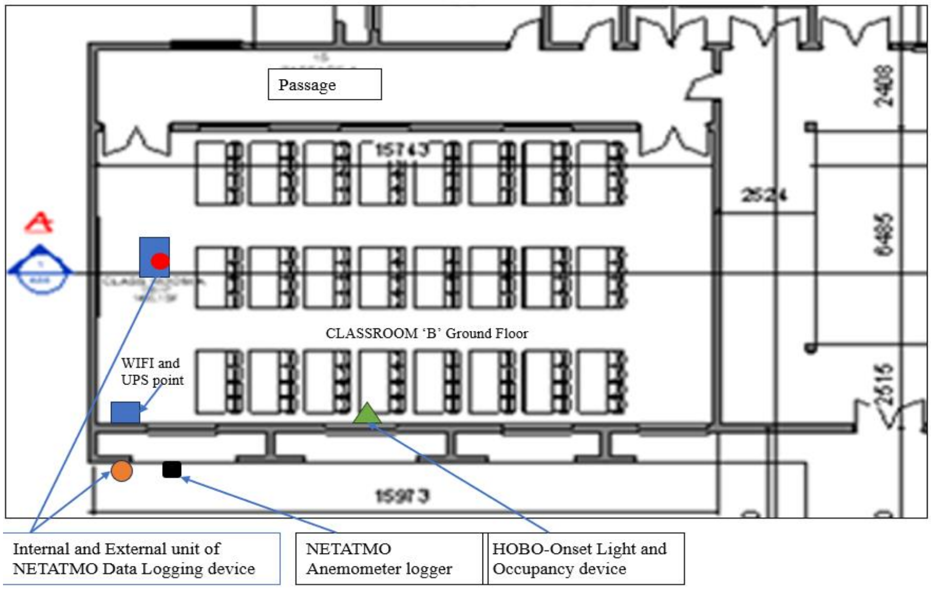

Figure 5-1(a) An experimental setup of data logging devices in Classroom 'B'.

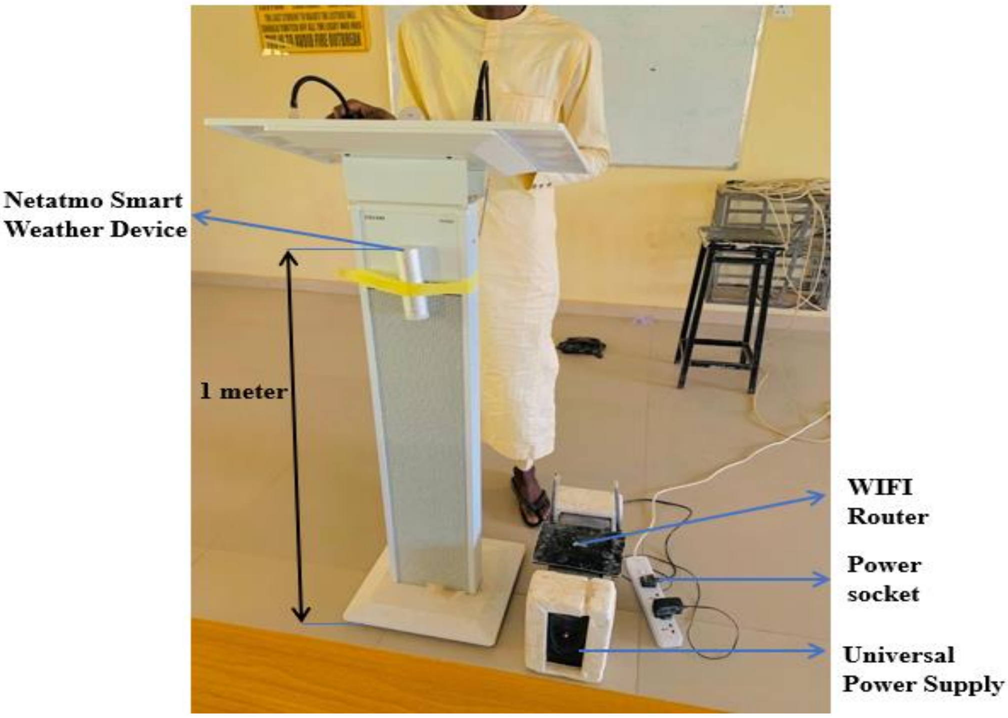

Figure 5-1(b) Picture View setup of data logging devices indicating the height of the NETATMO sensor.

5.2.2 Instrumentation Results and Discussions

The results of the experimental processes of data logging are analysed below.

i. Air Temperature

Figure 5-2 illustrates the result of measuring indoor air temperature, which indicates a pronounced daily growth in the indoor air temperature. The air temperature reached its highest on 21st April, reaching 45.3°C. The lowest minimum temperature in the month was 28.2°C. The difference between the maximum and minimum was steady between 2-7°C.

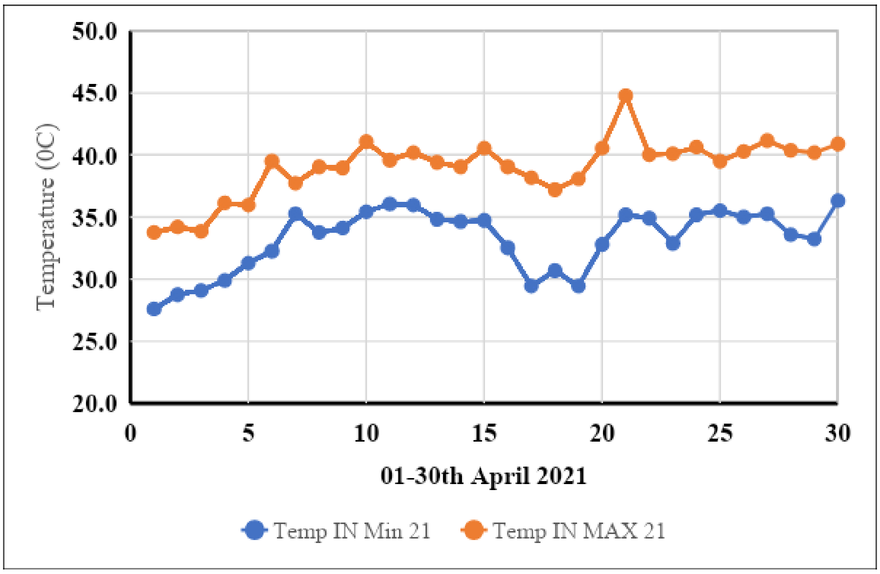

Figure 5-2 Monthly Indoor Temperature levels (minimum and maximum) in April.

According to Figure 5-3, the lowest and highest outdoor temperature readings were recorded during summer on the 4th and 6th days of the month, with outdoor temperatures reaching 46.2ºC and 47.1ºC respectively. Other rises were also observed, with temperatures reaching 44.8°C. The interaction between heat buildup infiltration and the inflow of hot air to interiors resulted in a temperature difference of around 10 to 12ºC between indoor and outdoor (max./min).

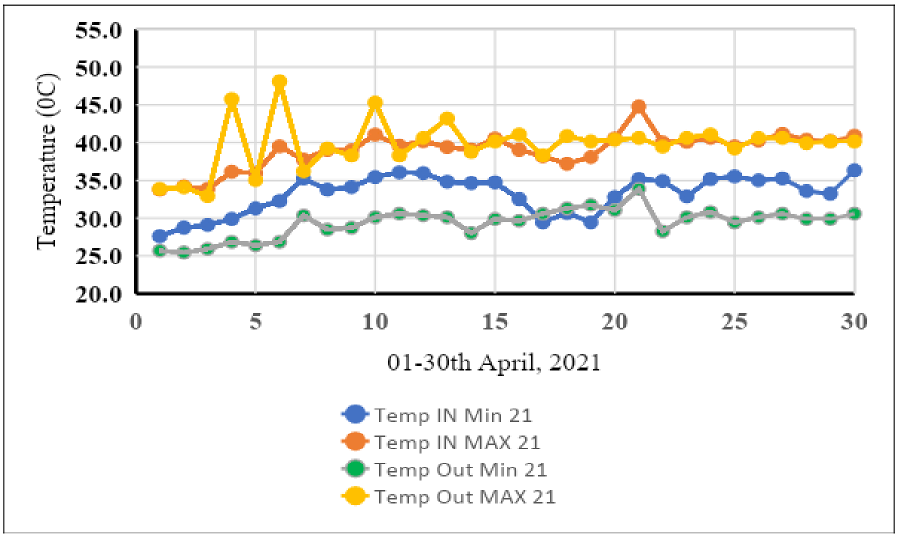

Figure 5-3 Monthly Indoor/outdoor Temperature measurement in the classroom; April.

ii. Relative humidity

Based on the ASHRAE 55-(2017) document's recommendation of keeping relative humidity in occupied spaces below 65% to prevent microbial growth, the classroom's relative humidity was measured and shown in Figure 5-4. The indoor maximum was 45.7%, the indoor minimum was 15%, and the outdoor minimum was within the comfort range. The air was exceptionally dry in the hottest month of April, with a monthly lowest level of 14.5% as recorded on the 14th and 13th.

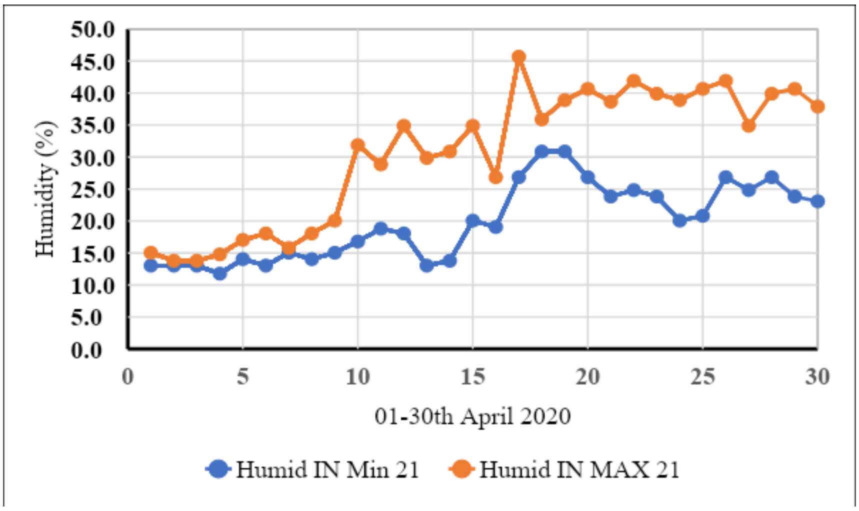

Figure 5-4 Monthly Indoor Humidity measurement in the classroom; April.

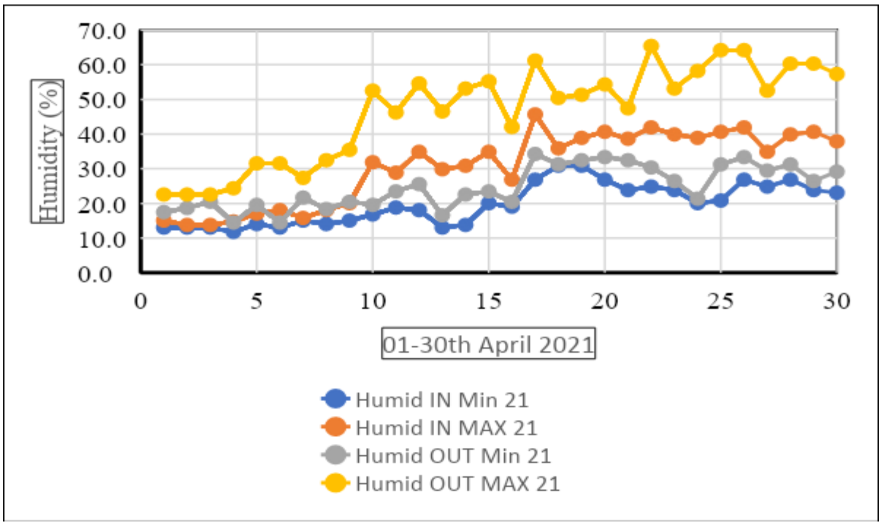

Figure 5-5 Combined Indoor/outdoor Humidity measurement in the classroom, April.

When comparing indoor humidity to outdoor data at their highest and lowest points, the humidity difference ranged from 2% to 20% during the day, as shown in Figure 5-5. To maintain thermal comfort, it is generally recommended to have higher temperatures to compensate for lower relative humidity (ASHRAE Standard 55 2017). Ventilation of the humidified space can be achieved through natural infiltration or a combination of natural infiltration and intentional mechanical ventilation.

iii. Carbon dioxide CO_2 and air quality

Throughout April, the classroom recorded a high concentration of CO_2 levels above the standard minimum threshold, ranging between 1575-1800 ppm. Figure 5-6 shows a surge in the total CO_2 concentration during the hottest month, with the hottest day recorded on 10th April at 1887.9 ppm, exceeding the prescribed limit of 1500 ppm in ASHRAE-55 minimum guidelines and EN ISO 7730. Despite having mechanical ventilation in the classrooms, the increased CO_2 concentration in the summer is due to the low ventilation air flow rate required to supply minimum fresh air for occupants. To improve the air quality, students should practice operating fans and air conditioners to increase the inside air volume. The concentration of anthropogenic contaminants (bio-effluents) responsible for deteriorating IAQ is closely related to CO_2 concentration (Freda et al., 2017).

Figure 5-6 Indoor Carbon dioxide (CO2) measurement in the classroom in April.

iv. Air velocity

In April, the air velocity stayed consistently between 0.5 m/s and 0.4 m/s at its lowest but reached maximum values ranging from 0.7 m/s to 3.3 m/s shown in Figure 5-7). To ensure good indoor air quality, ASHRAE Standard 62.1 (2022) recommends a minimum of 0.35 air changes per hour of outdoor air for residential buildings and 5-6 air changes per hour for most types of school buildings (excluding lecture halls). Other spaces like offices and shops also have recommended air changes per hour based on outdoor air ventilation rates.

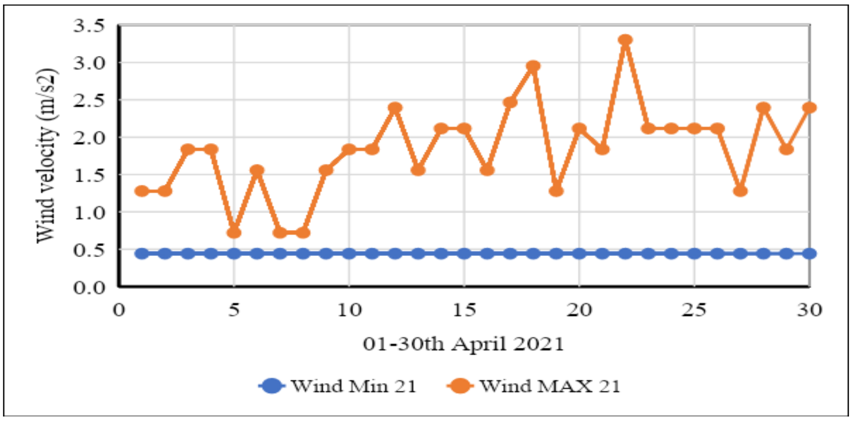

Figure 5-7 Outdoor Wind velocity (minimum and maximum) in April.

v. Noise level

In April, the classroom's noise level was less than 50 dB, indicating that it was relatively quiet during lectures and teaching activities throughout the month, as Figure 5-8 illustrates. However, in the winter, the noise level measured at 74 dB in December, which is higher than the regulatory standard of 47-56 dB.

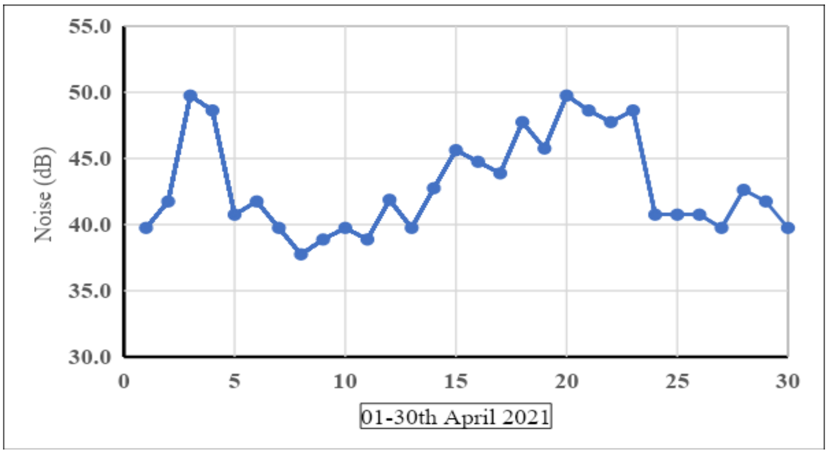

Figure 5-8 Indoor Noise (measured) in the classroom for the month of April.

vi. Occupancy and Lighting

During weekdays, the Lighting and Occupancy device shows that the occupancy rate in the morning ranges from 65.5% to 100%, except during the short break period from 8:00 am to 1:00 pm. There is another short break between 1:00 pm and 2:00 pm, during which all the classrooms turn off the lighting. The lighting is switched off from 6:00 pm until daybreak because there are no more classroom activities during these times. Therefore, there is only a limited need for artificial lighting in the classrooms since natural lighting is sufficient to meet the minimum lux level requirement of 350-500 lux during the day. On weekends, Figure 5-9 (B) the occupancy rate is 40-55% from 8:00 am to 10:00 am and 2:00 pm to 4:30 pm. This is mainly for students who participate in reading and small group assignments, after lecture which end at around 5:00 pm in the evening. Figure 5-9 (A) shows that artificial lighting is most needed in the classrooms for visual comfort; the air conditioning is to enhance occupants' comfort with cooling/ventilation.

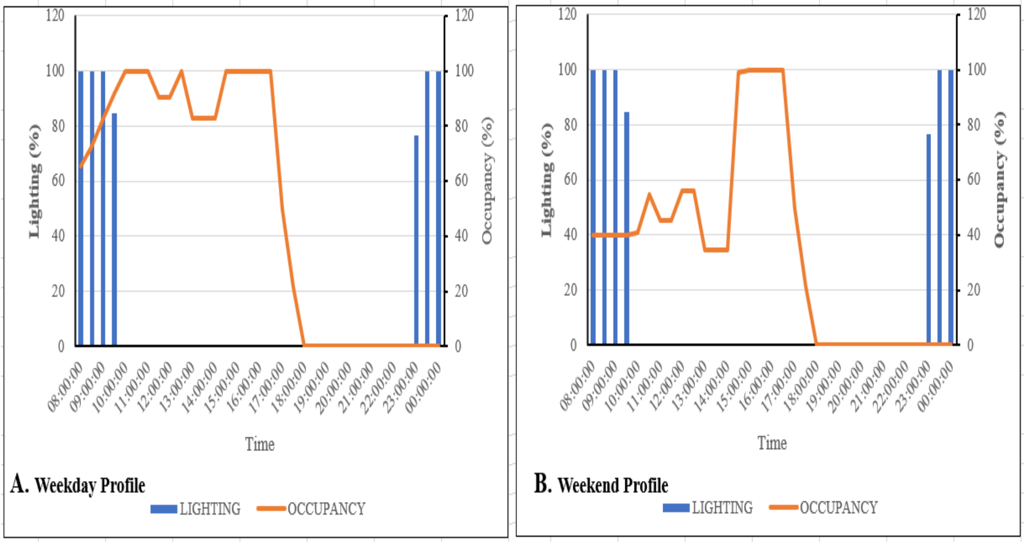

Figure 5-9 Lighting and Occupancy (HOBO logger); Weekday Profile (A) and Weekend Profile (B)

5.2.3 Analysis of results; Establishing Comfort Temperature

Instrumentation and monitoring of the classroom temperature from the data logger allowed using the mean air temperature recorded for every month to calculate standard effective temperature (SET) is a yardstick for determining thermal comfort in the learning space. A fixed temperature criterion was used to focus on the SET point, which has upper and lower limits and values for temperature inside the building to calculate comfort temperature. The calculated lower thermal comfort limit temperature illustrated in Table 5.1 for the month of March was 33.8° C lower, and the upper limit was 38.8° C; within these limits, the standard effective temperature (SET), and a comfort temperature of 29.1° C, relating to the conditions when the environment and the skin (body) temperature a neutral. However, the operative temperature set points lower and upper limits in the coldest month of January were 24.7° C and 29.7° C.

UTc: Upper Thermal Comfort Limit, UTc01= (Tn + 2.5) °C, UTc02 = (Tc + 2.0)°C **(5.1)**

LTc: Lower Thermal Comfort Limit, LTc01 = (Tn - 2.5) °C, LTc02 = (Tc - 2.0)°C **(5.2)**

The result shows that occupants' thermal comfort in a classroom building can be ensured through measurement to determine and by maintaining a higher standard effective temperature (SET) and comfort temperature (CT) throughout the year.

Table 5.2 Classroom SET and Comfort Temperature

(ASHRAE 55) Tn= 0.31Tn + 17.8				
	Upper thermal comfort limit, Utc	**Lower thermal comfort limit LTc**	**Monthly mean Temp, T_{om}**	**Comfort temp, T_{comf}**
Jan	33.7	28.7	31.2	27.5
Feb	36.8	31.8	34.3	28.4
Mar	**38.8**	**33.8**	**36.3**	**29.1**
Apr	**35.7**	**30.7**	**33.2**	**28.1**
May	31.1	26.1	28.6	26.7
Jun	32.1	27.1	29.6	27.0
Jul	32.4	27.4	29.9	27.1
Aug	33.6	28.6	31.1	27.4
Sep	36.9	31.9	34.4	28.5
Oct	34.8	29.8	32.3	27.8
Nov	31.6	26.6	29.1	26.8
Dec	**29.7**	**24.7**	**27.2**	26.2

5.3 Post-Occupancy Survey Evaluations (Interview and Questionnaires)

A questionnaire and a structured interview process were conducted with respondents for case study B (classroom complex) in the same way as in the previous chapter. Initially, occupants were informed about the building assessment goals and the impact of their behaviour on factors like thermal comfort, indoor environmental quality, and cooling load reduction. Teaching and presentations in university classrooms are common. During such activities, a seminar was held to invite students and staff to participate in online post-occupancy subjective evaluations of overheating in indoor learning environments. This personal engagement helps build evaluations and provides insights into occupants' experiences while receiving lectures indoors. It will also allow students and staff to impact and improve the building's operation positively. Achieving significant thermal comfort and energy savings depends on the behaviour of building occupants and the way the building is operated.

The online survey was conducted in four classrooms with a capacity of 100 students each. However, it targeted 121 respondents to evaluate and gather opinions regarding various environmental factors that affect the building's thermal comfort performance and energy efficiency during lectures from March to May 2021. Participants aged 18 to 68 completed an online questionnaire about their subjective assessment of indoor thermal comfort for 2 days, see Figure 5-10. The survey included questions about temperature, wind, solar, and moisture, previously discussed in a briefing and pilot study. The survey also considered the impact of these factors on an annual or seasonal basis. Students could indicate their preferences through votes on the PMV and PPD. Feedback was gathered on comfort, sensation, satisfaction, productivity, health/wellbeing (IEQ), building operatives that will improve thermal comfort provision, and cooling load reduction. The length of the heating season and its impact were also considered to help develop a cooling strategy.

Figure 5-10 Students participating in a questionnaire survey session in the classroom.

5.3.1 Interview structure

The interview survey questions were the same as those in Chapter 4 since the facilities are in the same environment. The building was supposed to be delivered through passive techniques.

5.4 Application of Thermal Comfort Perception Questionnaire

The survey was carried out during the summer season by administering an online Google questionnaire to participants who were occupants of the four different classes in the building. It was conducted in April between 12:00 noon and 2:00 pm, when students were fully engaged in their studies and when the outdoor temperature was at its peak. It also considers classroom teaching hours of 8:00-17:00. The survey's setting, processes, and conduct were the same as those in Chapter 4. See APPENDIX IIIA, which was also adopted for IVA.

5.4.1 Questionnaire Results and Discussion

Participants who initially expressed interest were asked to join a classroom session to answer questions about their perception of indoor overheating during hot summer months, specifically in April. 121 participants, including undergraduate students and academic staff from the Architecture, Building, and Quantity Surveying departments, completed an online Google questionnaire with education levels ranging from 100 to 400. Table 5.10 and Figure 5-11 illustrate the respondent's education levels. (See APPENDIX IVB Classroom Questionnaire Results; Tables).

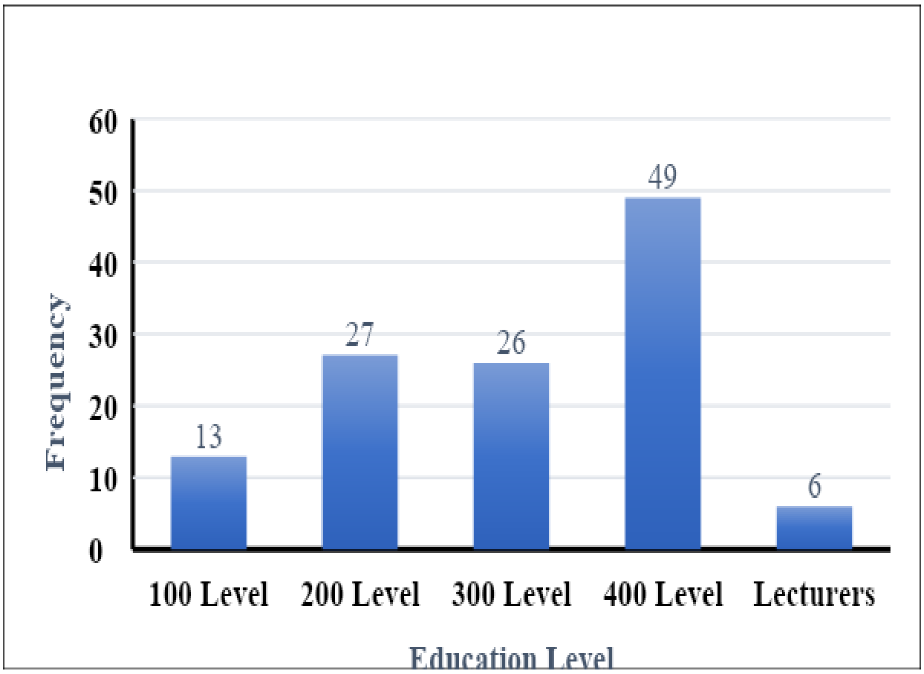

Figure 5-11 Frequency of respondent’s education level.

Table 5.3 Respondent’s education level

S/no.	**Level**	**Count**	**Percentage**
1	100 Level	13	11
2	200 Level	27	22
3	300 Level	26	21
4	400 Level	49	40
5	Lecturers	6	5
		121	**100**

The questionnaire assessed satisfaction, perception, and productivity on PMV and PPD scales to improve indoor environmental quality and thermal comfort. Due to the nature of the survey (online), the responses were 100% recorded.

The participants were male (74%) and female (26%). Participants (Staff and students). Shown in Figure 5-12.

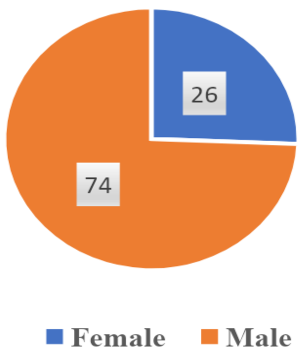

Figure 5-12 Respondents, Male and Female

i. Air Temperature

The overall occupants' temperature scores in the classroom were 76% on the 7-point scale, 31% very uncomfortable, and 18% slightly uncomfortable. Figure 5-13 Only 25% of the students were comfortable with the indoor temperature in the learning space.

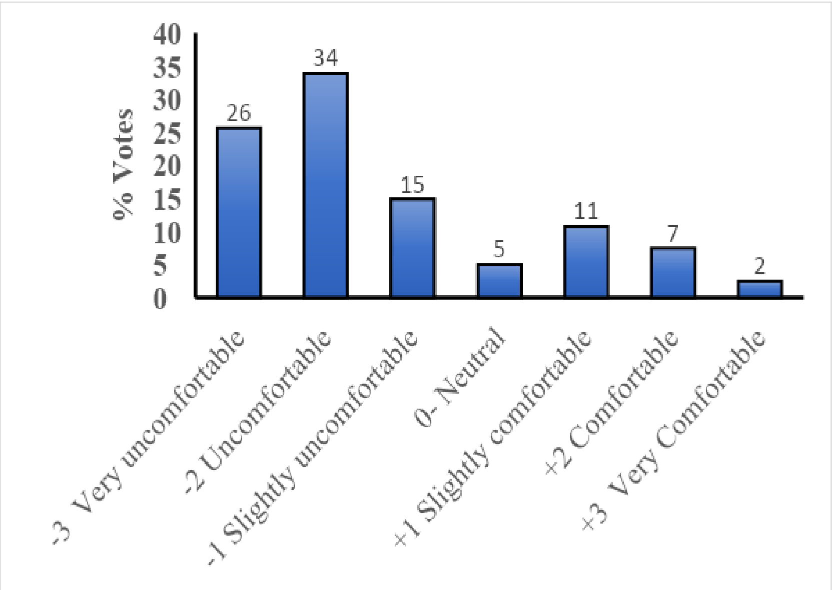

Figure 5-13 The percentage temperature sensation votes in Classrooms.

The 0.013 statistically significant (p-value) reaffirmed that the occupants perceive a significant temperature impact. However, this falls short of the ASHRAE-55 minimum PMV acceptance of 80-90%.

ii. Humidity

Out of all the votes cast, 77% indicated discomfort, while only 18% reported feeling comfortable. The remaining 6% were neutral and couldn't decide (as shown in Figure 5-14). However, the votes didn't meet the minimum requirement of the PMV/PPD acceptance range. Building interiors lack sufficient humidity in hot and dry climates because the air is dry for nearly eight months of the year.

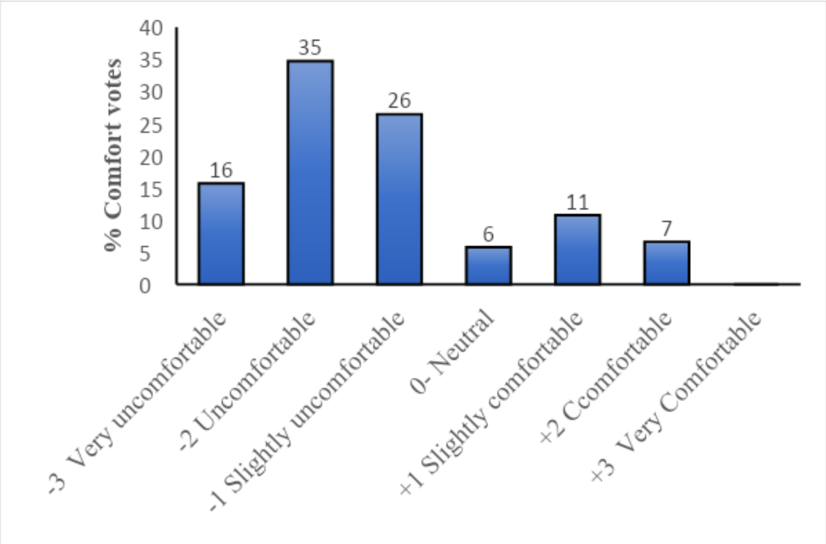

Figure 5-14 The percentage Humidity sensation vote in Classrooms.

iii. Air movement and quality

Figure 5-15 (A) displays the results of satisfaction votes for fresh air in classrooms. The data indicates that 73% of respondents were dissatisfied with the air buoyancy, 53% were extremely dissatisfied, 23% were overall satisfied, and 10% predicted neutrality. Additionally, the air movement is slow and polluted.

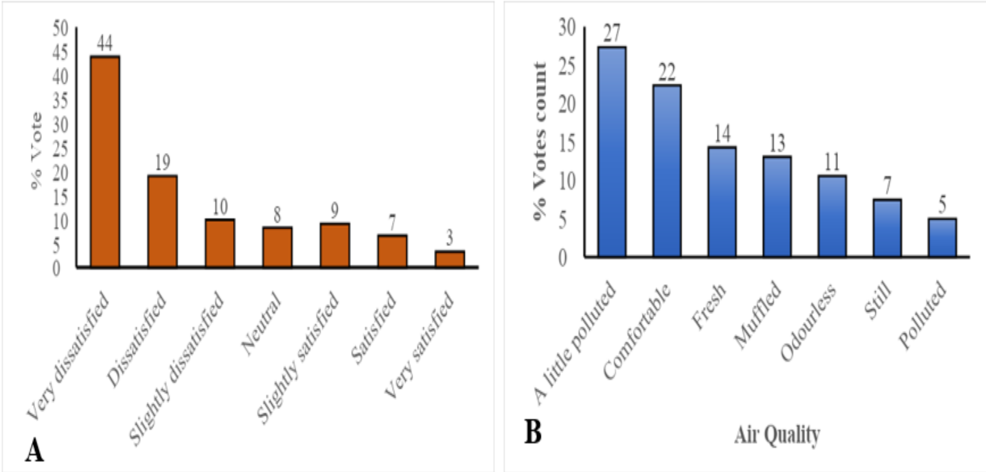

Figure 5-15 Thermal satisfaction with the supply of fresh Air (A) and Air Quality (B)

The questionnaire included two questions that addressed the overall air quality in the classrooms, fresh air satisfaction Figure 5-15 (A), and air quality perception. Respondents were given nine options to vote on, using a 7-point scale. Air quality is important as it measures the cleanliness or contamination of the air and its associated health impacts, Figure 5-15 (B) shows the air quality scores, indicating that the classrooms are polluted.

iv. Thermal Comfort Sensation in Seasons

In Figure 5-16, two questions were asked about how users perceive thermal comfort in indoor classrooms during hot (summer) and cold (winter) seasons. The results showed that occupants rated their overall thermal sensation at 96% during hot seasons and 86% during cold seasons. During hot seasons, both indoor and outdoor temperatures can be overheated, but occupants can adjust the indoor environment to remain comfortable using mechanical devices. In contrast, the cold season remains a significant factor affecting thermal comfort due to the high and low temperatures.

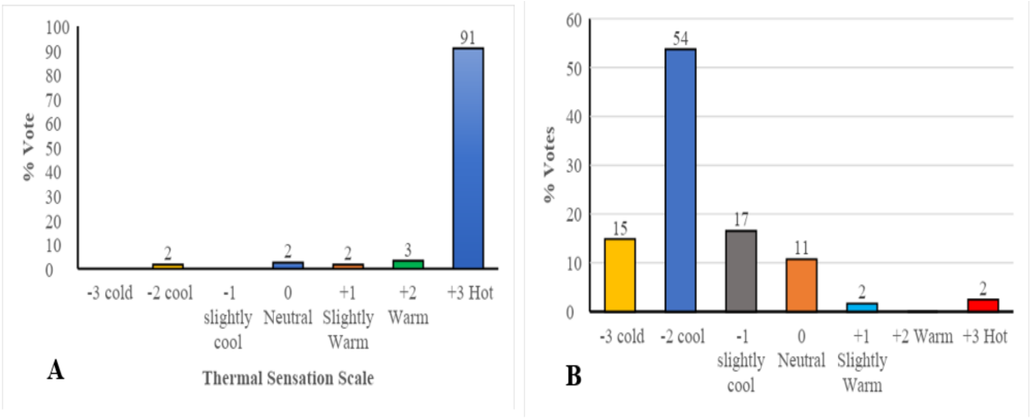

Figure 5-16 Consideration of thermal sensation in the hot and cold seasons.

v. *Health and well-being (IAQ)*

Figure 5-17 illustrates that when respondents were asked about any symptoms they experienced in the classroom, 37% reported sweating, 18% felt tired, 15% had headaches, and 12% nodded off. These experiences were more intense between 11:00 and 14:00 and 14:00 and 17:00. Respondents had the option to choose from various symptoms, and those who reported sweating were more likely to experience it between 11 a.m. and 5 p.m.

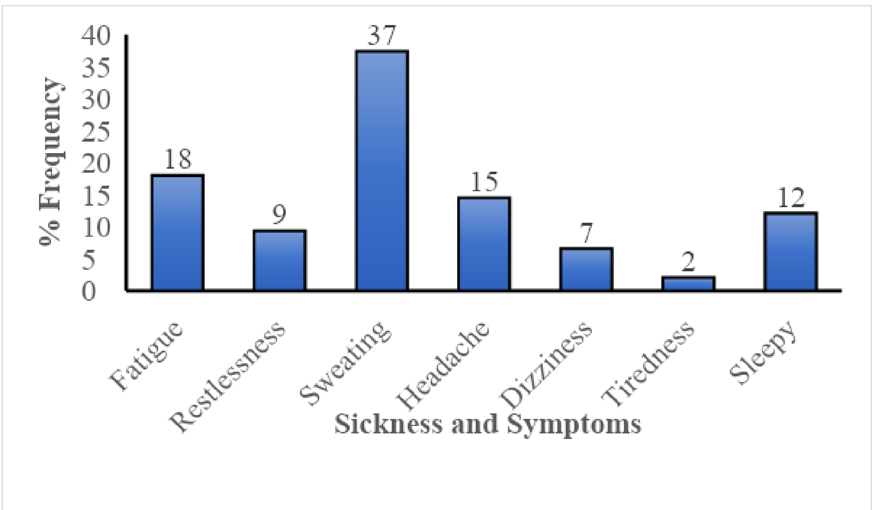

Figure 5-17 Ailments associated with Heat perception in Classrooms.

During a heatwave, six hours of sun radiation can cause pain, which could be a problem, hazardous for health in extremely hot, dry, and poorly ventilated, according to (MHCLG, 2019).

vi. Clothing

The survey on thermal comfort included a question about clothing preferences, as shown in Figure 5-18. Results indicate that 23% of male respondents voted for traditional clothing, while 36% preferred short-sleeved shirts and trousers. On the other hand, female respondents mostly voted for traditional garments (16%) and long sleeves (4%). It's worth noting that the survey period was considered since clothing preferences do not vary significantly across seasons. Students tend to wear clothing that reflects their culture and beliefs rather than following seasonal trends.

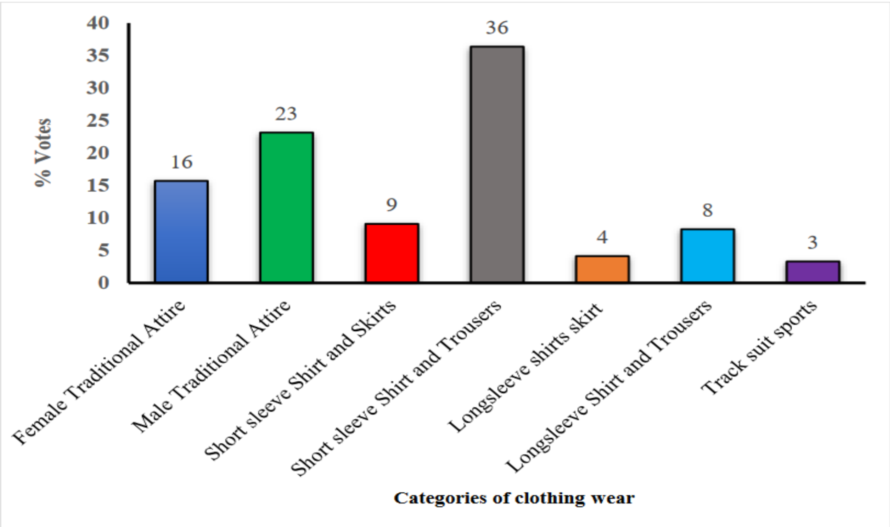

Figure 5-18 Clothing Wear by Survey Respondents.

vii. Productivity

Productivity is affected by both thermal comfort and activity level. Figure 5-19 shows the survey that not only asks about enhancement and interference but also asks occupants to rate the impact of indoor environmental quality (IEQ) in relation to work output, specifically whether the indoor conditions support or hinder productivity at different activity levels. During the summer, 84% of respondents said that IEQ conditions enhanced their productivity, while only 7% reported interference, and 8% were undecided.

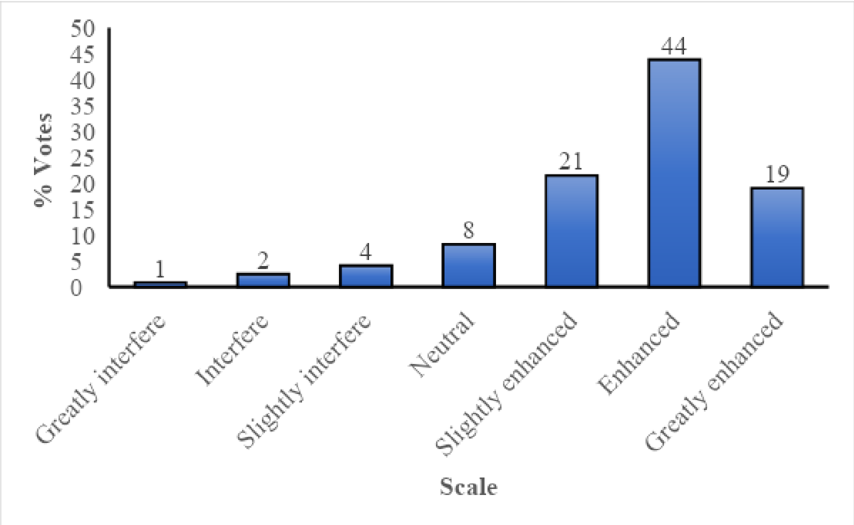

Figure 5-19 The percentage votes of occupant's performance and productivity.

viii. Building Form Appreciation

The building's interiors and exteriors were evaluated based on three main factors: architectural shape/geometry, form elements, and aesthetic appeal, as well as how the building was positioned in its environment. The occupants gave an overall satisfaction rating of 97% for the building's aesthetic appeal, 54% satisfied, 35% very satisfied, and 8% slightly satisfied with the orientation and positioning. Figure 5-20 illustrates the occupant's satisfaction with the form. ASHRAE Standard-55 (2017) and TM 54 acknowledge that poor indoor environmental quality can lead to discomfort and health issues, negatively impacting students' productivity.

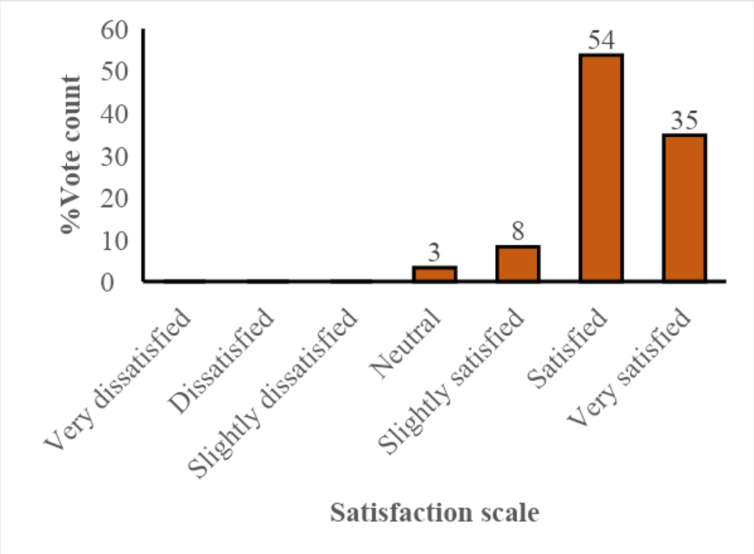

Figure 5-20 Respondents' percentage satisfaction with the built form.

5.4.2 SPSS Analysis of Questionnaire Results and Discussions.

The Kruskal-Wallis null test of the hypothesis was used to ascertain the significance level in each case and to justify the research questions from a statistical perspective. (See APPENDIX VB Questionnaire SPSS analysis; Tables).

Question 1: How similar (or close) are the distributions of thermal sensations in the hot season and thermal conditions in the winter/ rainy season? The Wilcoxon Signed Ranks Test is used because the level measurement of the categories is ordinal.

Table 5.4 Wilcoxon Signed Ranks Test

Related-Samples Wilcoxon Signed Rank Test Summary	
Total N	121
Test Statistic	5.500
Standard Error	361.052
Standardized Test Statistic	-9.544
Asymptotic Sig.(2-sided test)	.000

The test result from the population (N=121) proved that the null was rejected at a 5% significance level. Thus, there was a significant difference between the thermal sensations during the two seasons, this was because z-value= -9.500 at a probability of 0.000. Example Table 5.3, illustrates.

Question 2: Are there significant differences in the distribution of the measured thermal comfort parameters (i.e., temperature, humidity, satisfaction with the level of fresh air, comfortability of the lighting in the lecture room workspace and the satisfaction of the noise level in the indoor space) during the hot season? The appropriate test here is the Krustal Wallis Test because the level measurement of the categories is ordinal.

Null hypothesis: No significant differences exist in the measured thermal comfort parameters distribution during the hot season.

Conclusion: The result of the analysis indicates that among the measured thermal comfort parameters, there was a difference between the measured thermal comfort parameters in the hot season. The null hypothesis was rejected across temperature, humidity, indoor Air, and lighting where the *p-values* are less than 0.05; only noise level in the workspace was significantly above 5% level during the hot season. There was a difference in the distribution level of this parameter during the season.

Question 3: Are there significant differences in the distribution of the measured thermal comfort parameters (i.e., temperature, humidity, satisfaction with the level of fresh air, comfortability of the lighting in the lecture room workspace, and the satisfaction of the noise level in the indoor space) during winter/rainy season? The appropriate test here is the Krustal Wallis Test because the level measurement of the categories is ordinal.

Null Hypothesis: There are no significant differences in the distribution of the measured thermal comfort parameters during the winter/rainy season.

***Conclusion**:* The analysis results show that among the measured thermal comfort parameters, in the cold winter season, light ($p = 0.009$) and noise levels (p = 0.023) in the classroom spaces were significant $p = < 0.05$ (5%). The null hypothesis was rejected, showing a difference in the distribution level of parameters during the winter season.

Question 4: Is there a difference in the distribution of sitting arrangements for students in the lecture studio, considering the floor level? The appropriate test here is Kruskal Wallis. The measurement within the categories is ordinal**.**

Null Hypothesis: When considering the floor level, there is no significant difference in the distribution of sitting arrangements for students in the lecture studio.

Conclusion*:* The result shows that students' sitting positions were not affected by their feelings of thermal discomfort in the hot season because the test failed to reject the null hypothesis $p > 0.05$; it is expressed that there was no difference in the distribution of sitting arrangement for students in the lecture classrooms; meaning regardless of where the students sitting positions the thermal perception is the same in classrooms and across all floor levels.

Question 5: Is there a time in a day when environmental thermal comfort is the most important problem?

Null Hypothesis: Thermal comfort is the same across the time of day. The appropriate test here is Krystal Wallis. The level of the categorical measurement is ordinal**.**

Conclusion: The test result of significance shows two groups: Afternoon (11-2 pm and 2-5 pm); the null hypothesis was rejected at these times. The *p-values* = *0.002* and *0.000*, less than *0.05* during these periods as voted by the respondents. The thermal comfort was, therefore, not the same across the time of the day.

5.5. Summary of Measurement and Survey Data in the Classroom Complex

The instrumentation results determined that occupants' thermal comfort in a classroom building can be ensured through measurement and using indices to calculate both standard effective temperature (SET) and comfort temperature (CT) throughout the year. The occupants in the classroom experience different levels of discomfort and heat stress based on the seasons. Hot temperatures are felt During the summer, while dryness is felt in the winter. However, the perception of comfort concerning clothing is insignificant because clothing worn is linked to people's culture. To prevent overheating, it's important to analyze thermal comfort. Mitigating the indoor environment can help address each person's unique thermal perception, improving the building's structure, and IEQ. Overall, the statistical analyses have supported the rejection of null hypotheses, highlighting variations in thermal comfort parameters based on season, classroom setting, and time of day. These findings are valuable for optimizing indoor environmental conditions and improving overall comfort in the building.

CHAPTER SIX

6. COMPUTER MODELLING AND PARAMETRIC ANALYSIS OF ENERGY PERFORMANCE AND THERMAL COMFORT: CASE OF THE ARCHITECTURAL STUDIO COMPLEX

6.1 Introduction

This chapter describes the selection and utilization process of the simulation software Integrated Environmental Solution, Virtual Environment (IESVE) and its applications in generating and calibrating a building model for thermal comfort and energy performance assessment.

Table 6.1 The Parametric Test and Process

S/no	Parametric Test	Process and Analysis
1.	Building Modelling Calibration	Design of simple model, energy model, input building specs., fabric construction, and materials template
2.	Fabric Gains Test	Testing internal and external gains
3.	Natural Ventilation and Infiltration Test	Natural, auxiliary, and infiltration rates.
4.	Glazing Test	Testing glazing types in varying specifications.
5.	Shading Test	Windows, roof, canopy, and vegetative.
6.	Optimization of Building Cooling Load	total building cooling plant sensible load after each iterative design change
7.	Building Upgrade and Maintenance	Applying optimal results to develop maintenance and retrofit framework
8.	Renewable Energy	Solar PV panel integration will improve energy supply.

This also explains the stages of parametric analysis and passive diagnosis of the studio building's indoor environmental quality. It also involves maintenance improvements that deliver the occupants' indoor comfort conditions and cooling load reduction through passive retrofit strategies. The parametric tests to be conducted include Building Modelling Calibration, Fabric Gains Test, Natural Ventilation and Infiltration Test, Glazing Test, Shading Test, Optimization of Building Cooling Load, and Building Upgrade and Maintenance.

The process involved in the simulations is detailed in Table 6.1. The simulation process included iterative design changes to assess their impact on cooling load, occupants' comfort, and fabric gains. Changes were made in a specific order to maximise their potential. For example, after increasing thermal mass, natural ventilation was introduced, and night cooling was implemented after adjusting u-values. Infiltration was then adjusted to reflect improved insulation. Window efficiency was improved, and shading was added to reduce incident radiation and solar gains.

6.2 Parametric Process of Architectural Studio Building

The parametric analysis was conducted using IES-VE computer software. The case study involves assessing thermal comfort and energy efficiency of a studio complex to achieve indoor environmental quality (IEQ), occupants' health/well-being, and strengthening environmental policy.

6.2.1 Simulation Basis

The passive design process was recognised as one of the approaches for addressing thermal comfort and overheating in buildings in hot, dry climates. The main objective was to utilise passive technologies to improve the performance of building forms for solar heat control by providing external shading elements and thermal comfort optimization of indoor learning space of building applicable to the location of Birnin Kebbi, Nigeria. This research used ASHRAE and CIBSE guidelines as minimum standards because the Nigerian Building Energy Efficiency (BEE) guideline document is still being developed.

The NESP and BEE are the country's two regulatory documents recommending strategies and techniques for improving building performance and efficiency. However, this will help bridge this gap in the existing literature; simple maintenance frameworks were developed to help built professionals provide the minimum thermal comfort by altering the building fabric elements, different types such as the provision of external shading devices, glazing types, shading the roof by laying photovoltaic (PV) panels at the rooftop while servicing as a renewable source of energy. The Climate Consultant prescribes horizontal shading elements most effective in the climatic zone.

Shading against solar radiation is a viable passive building retrofit and maintenance strategy in hot/dry climates (Dabaieh et al., 2015 and Hausladen et al., 2011). A series of dynamic simulations were run on the studio building to derive the fabric elements' average monthly solar heat gain values from ascertaining how solar insolation affects different sides of the building, specifically where openings are against the orientation and the indoors of buildings and how overheating affects the occupants (staff and students) for a typical year. Other fabric elements such as roof, window and glazing were assessed and improved. Structural shading devices were developed in window positions, and a simulation was carried out for retrofitting and maintenance.

6.2.2 Simulation Software IESVE

Integrated Environmental Solutions Simulation, virtual environment Software (IES-VE), is the comprehensive thermal and energy simulation analysis tool used for the parametric assessment of the educational/ learning buildings in this research section and the subsequent chapter. According to Corrado and Fabrizio (2019), the IES-VE simulation tool is a collection of applications that can be used in conjunction with one another to solve various issues. Various applications, including model builders, energy, cost, etc., can be used as categories of applications in VE. One application's output data could become another's input data. However, Mihara et al. (2019) lamented that VE software is comprehensive and often creates a thorough approach to the performance assessment of buildings by combining data from the HVAC and ventilation, daylight, artificial lighting, and CFD sectors (active and passive) energy sources thereby giving the information needed to make more responsible judgments. The optimal requirements and solutions provided by the IESVE software can be specified by knowing what works best for occupant happiness and significantly greater energy efficiency (Vethanayagam and Abu-Hijleh, 2019; Lau et al., 2016). The importance of IESVE simulation software for thermal comfort assessment and energy efficiency analysis is realised efficiently for the dynamic simulation technique employed in this study to address the key factors associated with the energy efficiency and building form's performance improvement. Adopting the IES-VE modelling tool made it easier to develop a model because it's a full package software with a modeller; ModelIT, and other ranges of simulation interphase such as SunCast, MacroFlo, FlucksDL, LightPro and RadianceIES, all under lighting and ApacheHVAC, MacroFlo for energy and ventilation modelling and Apache and VistaPro as main simulation engines for carrying out all forms of simulations in the VE, that allows the 3D design of a model and analysis under the same simulation package. (Weytjens et al., 2011; and Bahar et al., 2013).

According to Alqadi et al. (2021), the software's validation accounts for its ease of usage, interoperability advantage, and graphical output friendliness in the focus of architectural and focused engineering research. The IESVE- software 2019 Version was used in this research. Its range of applications and simulation platform for various thermal indices assessment, natural ventilation techniques, and modeller was used to model the building fully. The thermal performance of the higher education facility was assessed using the simplified architectural models that had been developed. The Architectural Studio complex was fully modelled in VE to avoid a large margin of error associated with the Building Information Modelling (BIM) importation and integration process. Alqadi et al. (2021) further say simplified building models developed in IESVE do not require additional BIM inputs; they require fewer inputs and provide a better connection between the direct and outcomes.

The main objective of this parametric study was to quantify the effects of implementing the chosen passive strategies on the university (teaching and learning) buildings in the hot-dry climate of Nigeria, demonstrating the passive design potential to reduce indoor overheating during the extreme (hottest) times of the year through the cooling process. Based on the results presented in Chapter 3, which were also discussed in a paper developed as part of this study entitled "Review of Strategy for Assessing the Thermal Performance of Institutional Building Form in Hot-Dry Climate of Nigeria", Bena et al. (2019)It was highlighted that the use of multiple methodologies would make an effective strategy for the passive assessment of higher education buildings and would significantly contribute to finding solutions to improve indoor thermal conditions for occupants, reduce overheating, and improve the indoor environmental quality of buildings in Nigeria's hot/dry climate. The parametric study in Chapter 5's simulations lays the groundwork for the structure's maintenance and retrofitting.

The IESVE simulation was performed for the following input parameters: Typical meteorological year (TMY) weather data for the Birnin Kebbi city locations. Independent variables include Form geometry, construction materials and considerations for the surrounding environment. The dependent variables assessed were solar radiation, active cooling energy reduction, building performance on indoor air quality, lighting energy, ventilation, building system (HVAC), Set-points, internal gains and improved indoor thermal comfort, as suggested in research by (Elzeyadi & Batool, 2017). The following building assessment and parametric tasks were performed at different stages.

6.2.3 Building Modelling with Model IT Application.

The ModelIT application is a highly advanced tool that enables users to incorporate intricate design details throughout the modelling process. It is the primary modelling tool for importing, modifying, and enhancing building geometry from 3D models generated by computer-aided design (CAD) or building information modelling (BIM) software. Users can effortlessly generate three-dimensional building spaces based on the outlines by simply attaching drawing exchange (DXF) files to the provided tools. This app also offers access to dynamic data visualization, with pre-set and custom views available. With ModelIT, users can develop performance analyses and access related building information.. (IESVE, 2020 and IESVE, 2012). However, the model designs of the case study buildings created using ModelIT were subjected to parametric thermal and energy simulation analyses to ensure that the building form provided optimal comfort and reduced cooling load.

6.2.4 Sun Cast Application and analysis.

The IESVE software tool SunCast is specifically designed for solar exposure analysis. This powerful tool accurately calculates the sun's position in the sky, tracks solar penetration throughout the building's interior, and even considers shadows. SunCast can assess shading against solar light and the impact of surrounding terrain and buildings when used with the Apache Dynamic Simulation application. The application also generates various animated, visual, graphical, and numerical outputs, making it an incredibly versatile tool (IESVE, 2020c). SunCast application is used to analysed solar gains and shading performance in buildings. It is the first step in simulation. Shareef and Altan (2021), found that designing buildings along the East-West axis minimises solar exposure. However, long facades facing the North-South axis present unique challenges.

6.2.5 Apache Sim application.

ApacheSim is used to run a dynamic thermal simulation. It is an application programme at the heart of any simulation in IESVE software that relates to a building's sustainability and energy efficiency from the energy or carbon usage standpoint. ApacheSim complies with many international building rating requirements that guide built environment professionals in decarbonising buildings. Apache system is used in all IESVE interphases and can be accessed directly from the toolbar or the building template manager IESVE. The "APACHE Application" from IESVE Software offers an accessible graphical user interface (GUI) for the Apache engine and enables users to input data, visualise and access to man VE functions. IESVE findings are more accurate in dynamic performance calculations than the other applications, such as EnergyPlus, according to (IESVE, 2020c; Tee et al., 2020).

6.2.6 MacroFlo Application for Ventilation

This application is used to analyse the performance characteristics of various types of façades and the analysis of air velocity through the building openings. It is achieved in conjunction with the Apache HVAC system application. Computational fluid dynamics (CFD) is a simulation methodology employed using MacroFlo interphase in IESVE to study buoyancy-driven natural ventilation, air flow and heat transfer processes occurring within and around building spaces and within indoor or outdoor areas. The CFD techniques are becoming an alternative and common method to investigate natural ventilation in buildings given specified boundary conditions, which include climatic effects (Almhafdy et al., 2015). MacroFlo applications are used in the analysis of infiltration, natural, and mechanical ventilation on airflow/movements and temperature in buildings towards achieving the provision of natural ventilation, (IESVE, 2014).

6.2.7 FlucsDL Application for Lighting

FlucsDL is an application used to perform lighting calculations in VE. The interphase contains the menus and toolbars for point-to-point analysis on single or multiple rooms, specifically those with similarity. FlucsDL analyses the daylighting and illuminance factor of the indoor space due to window placement and surface reflectance of the analysed model based on the model’s disposition along its axis. It offers a dialogue box for the selection of sets, setting custom attributes, assigning templates, and assigning surface types; the result is in Lux (IESVE, 2016).

6.2.8 Climatic input data for simulation

The simulation procedure discussed in this chapter and chapter 6 was restricted to using climatic data of Birnin-Kebbi, the hot-dry climate of Nigeria. The site's precise coordinates are 04.1526035°E (longitude) and 12.332845°N (latitude), with an altitude of 214 meters. The Energy Plus database (U.S. Department of Energy, 2021) provided the Climate input data for the IESVE in the Energy-plus weather (*epw*) format for the weather data location at Sokoto International Airport, Nigeria. The key factor influencing a building's thermal conditions is the outdoor climate (Ferdous and Gorgolewski, (2014).

6.2.9 Studio Building Specification for Modelling.

The Architectural Studio complex (First case study) is a simple two-level structure with a floor area of (1856.14 m^2), External Opening Area/Glazing (249.97 m^2), and Window ratio of (319.72). Constructed primarily for students of Architecture, it has 4 studios and 2 supportive halls (modelling and computer), 2 studios on each level, storage and data rooms, toilet facilities, staircase halls, and a common walkway. The 400-level studio was chosen for the parametric process, and it is used as a unit extended to the whole building to assess the form performance in providing thermal comfort and cooling load reduction. Although the studio complex has no energy rating, the orientation renders the indoor prone to overheating. Three steps in the modelling process are:

- **i.** Base case modelling and simulation
- **ii.** Simulation and with modified variables
- **iii.** Simulation of the optimal case.

6.2.10 Building Modelling Considerations

Due to the capabilities and input requirements of the IESVE software, various assumptions had to be made when modelling and simulating the building's performance.

- **i.** The Birnin Kebbi weather file is used for all simulations.
- **ii.** The model was generated using the ModelIT app of the IESVE software.
- **iii.** The case study document did not include the original fabric specifications; these have been assumed to be together with the corresponding u-values.
- **iv.** Each unit space is a zone. Studios zones were the focus of the simulation.
- **v.** All floor levels were independent; door access between them was not considered because internal openings have less simulation impact.
- **vi.** The ventilation and infiltration procedures have been standardised with set values.
- **vii.** Because Low-E materials cannot be modelled, the same heat transfer coefficient has been represented exclusively by the accompanying u-values and g-values.
- **viii.** The corrugated (textured) materials have been depicted as flat rather than represented. These are the required assumptions made in achieving the design of the building model for carrying out parametric analysis based on (IESVE, 2020a).

6.3. Methodology for Building Simulation

The building model was designed using the ModelIT application of IESVE software as illustrated in Figure 6-1. The simulation begins with the assigning of building physical data (wall, floor, windows, and roof) and u-value specification in model design. This is followed by assigning a weather file initially integrated as input data into the VE through the *Aplocate* app and synchronized. It provides a typical metrological year (TMY) data extracted from multiple-year readings of weather stations across urban cities (Elnabawi & Hamza, 2022 and Lorna, 2016).

The material specifications and thermal values are inputted in the interphase on the VE construction template manager, generating building geometry. Before the second simulation stage, the standard construction/thermal templates are assigned. The second stage involves sun cast simulation to determine solar insulation, shading, and energy and MacroFlo application to determine ventilation, cooling setpoints, and infiltration gains.

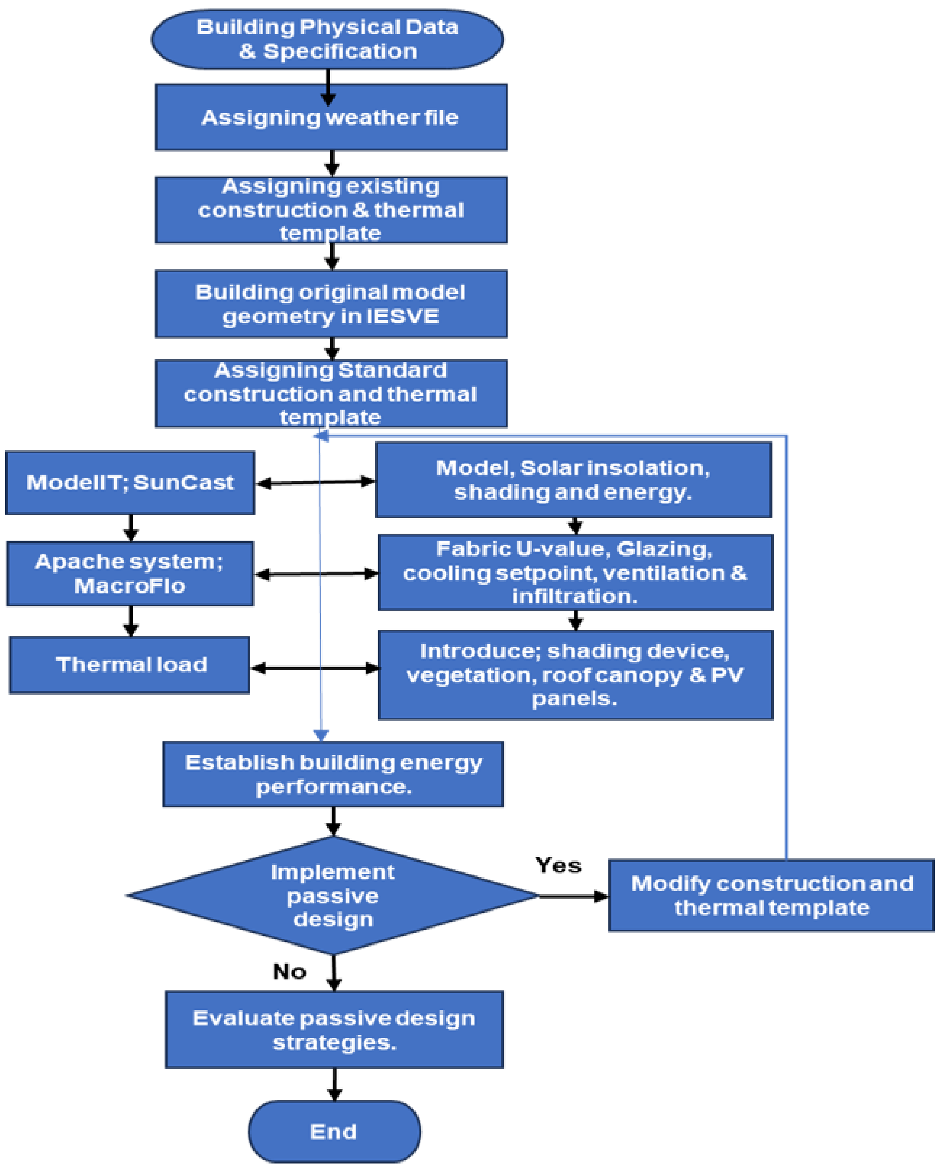

Figure 6-1 Flow diagram of the methodology using IESVE.

The energy (thermal load) analysis to obtain cooling load was subsequently carried out via fabric element simulation. Energy generation is also carried out by integrating PV panels through guided specifications. Heat loss and gain strategies were investigated to slow heat transfer into the building by conduction, convection, and radiation. A repeat of the passive iteration process is continued by changing the fabric values through the iteration process, and when satisfied, the end process is achieved.

6.3.1 Parametric Analysis of Building Model

The parametric analysis for the assessment process of the building model from the flow chart will target the following 7 to 8 headlines: building design modeling and calibration, fabric gains test, natural ventilation and infiltration test, glazing Test, shading test, optimization of building cooling load, and building upgrade and maintenance. All are aimed at improving the building's performance and efficiency.

Table 6.2 General Specification of Architectural Studio Building Source: (IES-VE Model).

	Building Name	***Architecture Studio Complex***
1	Total Functional spaces	24
2	Total Volume (m^3)	5018.97
3	Total Floor Area (m^2)	1455.71
4	External Wall (m^2)	1582.04
5	External Opening Area/ Glazing (m^2)	249.97
6	Total Wall/Window Ratio	319.72
7	Studio 400L FF Floor Area (m^2)	160.37

Table 6.1 shows the general specification for the streamlined model created in VE. It represents the studio model indices and values for all spaces, area, volume, and wall-to-window ratios. Figure 6.2 shows the simplified geometry views of the studio building model created using ModelIT. It shows the studio building design with simple details and the impact of morning sun shadow disposition, The A; South elevation, B; East elevation, C; North elevation and D; Roof plan

view. The geometric model viewer app access presents the designed model in material colour and energy-based colour or wired frame. The interphase has a navigator for daylighting and seasons and the interphase for viewing the solar angles.

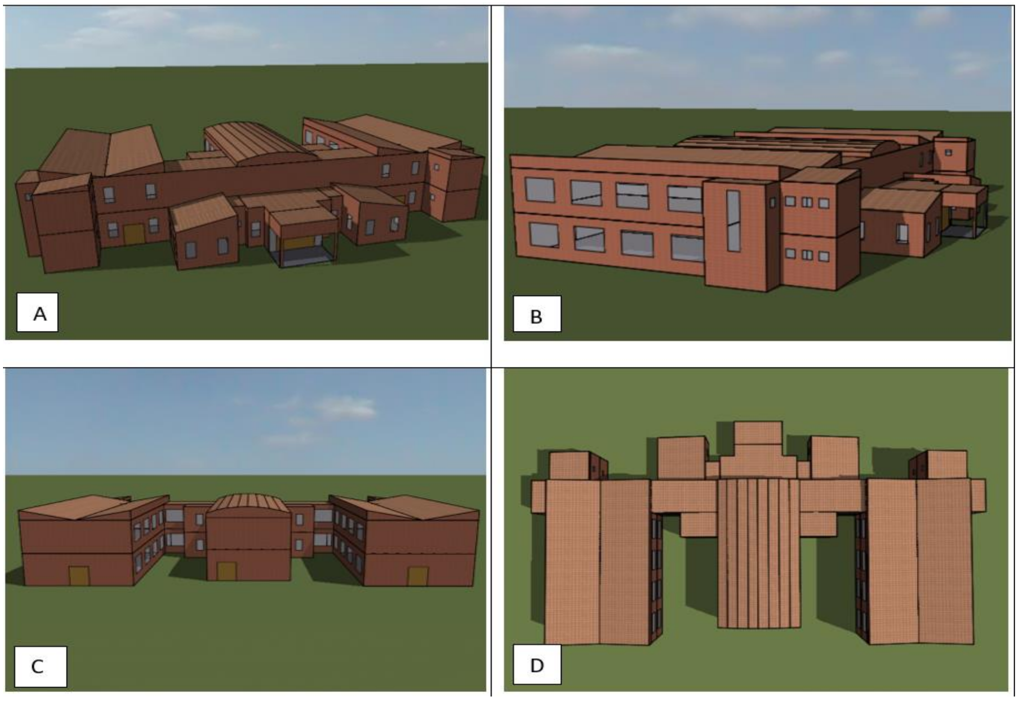

Figure 6-2 Existing Simplified Model Geometry Architectural Studio Complex building; A; South elevation, B; East elevation, C; North elevation and D; Roof plan view.

6.3.2. Sun-Cast Modelling

Figures 6-2 and 6-3 depict the sun's position at 09:00 am on the equinox, March 20 (equinox). At that time, the Sun's shadow angle was 45°, and during an especially intense summer, the solar altitude angle reached 71° by noon. This analysis indicates that the building has limited self-shading capacity, as the shadow was cast westward. The building's isolated geometry and self-standing studio design, combined with its east-west orientation, contribute to significant indoor overheating before noon and until 17:00. Consequently, occupants of the studios will experience discomfort due to glare from the morning sun and intense heat in the evening, with the western façade allowing substantial heat penetration through the windows. The IESVE Model sun cast indices align with the Andrew Marsh sun path values detailed in the previous chapter, confirming the outputs generated using the VE sun-cast application.

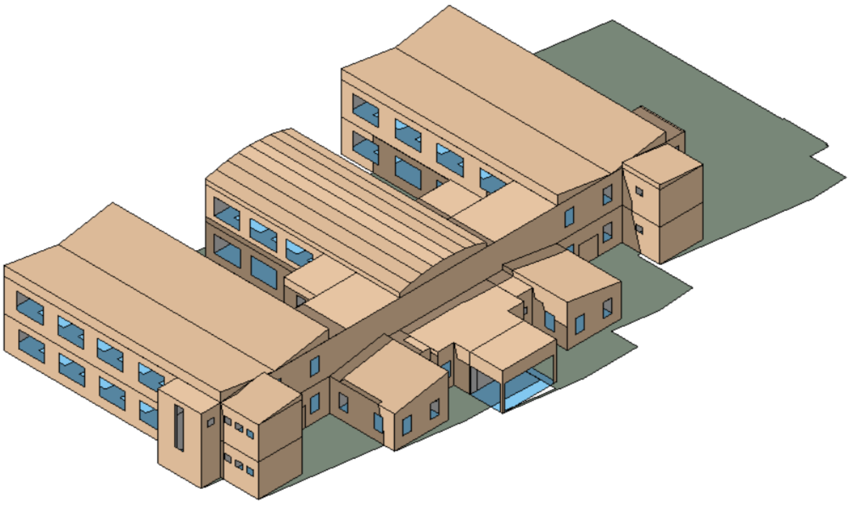

Figure 6-3 Sun-Cast model Solar shade at 9:00 am at 45° NE angle on 20th March Equinox

6.3.3. Assigning Construction and thermal template

Assigning construction materials and thermal templates begins with the initial fabric U-Value input. The process of reflecting the existing building situation in the template manager was achieved by activating Apache construction for the whole building simulation. By adjusting the values in' Building Template Manager, ' adding and reducing the values of specific elements was explored to test envelopes' response to thermal capacity and specific heat.

i. Construction Template

The construction database from the building template manager was used to assign construction element types and sizes for the studio model. Considerations were made because the studio complex has no adjacency effects for shadow/shade advantage or absence of vegetation; the building stands alone on the site. This condition was used in the model input in the setup. The fabric specifications and u-values information on construction elements and compositions in Table 6.2 were obtained during the survey study. The associated materials values in the construction template manager via Apache Pro application, each value of building elements such as the solid structural wall with a thickness of 260 mm inclusive of rendering, floors (ground and upper), roof, internal ceiling, external doors, and windows glazing specifications, sizes, U-value (W/m2K) and thermal mass in Kg/ (m2.K) were reflected and assigned.

i. *Thermal Template*

The building's operating parameters were set using 'Building Template Manager.' Input includes occupancy profiles, lighting profiles, air exchanges, building activity, and internal gains. These design conditions were kept constant throughout the building optimisation. The loads or gains parameters are changed only when physical amendments are made.

Figure 6-4 A shows the occupancy profile set for the building on weekdays, and (B) shows the occupancy profile set on week-end days for the design studio. Weekends for design practicals considering the building function, for teaching, learning, and design, it is most likely that the operating hours stay this way for most weeks of the year; this was a function unique to the design courses offered by the faculty of Environmental Sciences of the University, example design/construction presentation that last longer in time allocation. However, the building is at full occupancy between 9 am and 5 pm and half occupancy to account for people's lunch-break period before returning for lectures until the end period. Weekend days account for half occupancy in 24 hours.

Table 6.3 Building fabric and Construction materials specification.

S/No	Construction Elements	Description of Construction elements in (mm)	U-value (W/m^2K) R-Value	Thermal mass CM (J/K)
1.	External wall	Masonry-2700mm; Plastered Ext. Wall Ext. Cem. plaster 20; Conc. Hollow blck, 230; Inte plaster, 20. =270.	1.43 0.53	138.00
2.	Ground Floor	Conc. Tile 10; Cemt screed 20; Dense Conc. slab,150; PVC DPM 0; Sand fill/gravel fill 120; Hard C/ layer 300. = 600	1.71 0.17	187.74
3.	Roof, Structure	Aluminum L/span Corr. roofing sheet 0.045; H/Metal roof member.	7.14 0.0001	6.55
4.	Ceiling	Suspended Ceiling particle board; 18	4.04 0.05	8.47
5.	Upper fl/Ceiling	Concrete tiles 10; Cement/sand screed 20; RC L/W concrete slab 150; C/plaster (render) 20. =200	1.91 0.32	130.00
6.	Internal Wall	Masonry-2700mm; Plastered Extern.Wall Ext. Cem. plaster 20; Conc. Hollow block, 230; Intn. plaster, 20. =270.	1.26 0.53	138.00
7.	External Door	Outer surface plate; 3.2; Frame cavity 40; Inner surface plate, 3.2.	5.88	5.99
8.	Window Glazing	5mm Single glazing with blue coating mild tint in Aluminum frames (Net U-value wt frame) = 5.17	5.69	G-=0.48 Transmit tance e (T) 0.76

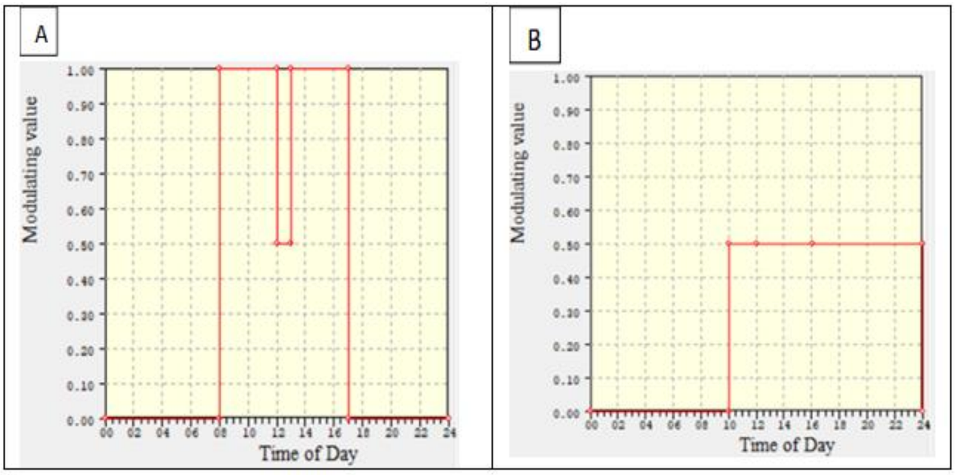

Figure 6-4 Daily weekday occupancy profile, (A) and Daily weekend occupancy profile, (B).

ii. Assumptions

- The cooling set point was turned off for all simulations, as this report aims to investigate passive cooling strategies. Where the reduction in cooling load has been used to demonstrate these effects, the cooling set point has been set in association with the occupancy profile.
- In line with the 'Effective Temperature Index of indoor thermal comfort for educational buildings in climates', proposed in ASHRAE handbook, (2021), the set point is at 26°C.
- Cooling set point to be turned off during simulation.
- The building's internal gains and air exchanges were set in with a variation of the new annual occupancy profile, Figure 6-4 (A, B), in line with CIBSE Guide A, (CIBSE GUIDE A, 2021).

Tables 6.3 and 6.4 show the system input parameters for plug-load (power), lighting, ventilation/infiltration, and people gains.

- **i.** Maximum power consumption=15W/m2
- **ii.** Maximum sensible gain for fluorescent light =12W/m2: People=60W/person.
- **iii.** Maximum latent gain: Person= 60W/person
- **iv.** Maximum sensible gain: Person= 90W/person.

v. Auxiliary Ventilation: Maximum flow =10-unit l/s/person on new annual profile at external adjacency conditions.

vi. Infiltration maximum flow = 0.5 ach unit on continuous profile as above.

vii. However, changes to settings were made by adding to an existing case.

Table 6.4 Template input of plug load density and power consumption.

Computers

Reference	Type	Assigned to Templates?	Input Mode	Maximum Sensible Gain (W/m²)	Maximum Sensible Gain (W)	Maximum Sensible Gain (W/person)	Maximum Power Consumption (W/m²)	Maximum Power Consumption (W)	Diversity Factor	Radiant Fraction
STUDIO 4 PLUG Load density	Computers	☑	W/m²	0.000	-	-	15.000	-	1	0.22

Table 6.5 Template input, general lighting, and power consumption setting.

General Lighting

Reference	Type	Assigned to Templates?	Input Mode	Maximum Sensible Gain (W/m²)	Maximum Sensible Gain (W)	Maximum Sensible Gain (W/person)	Maximum Power Consumption (W/m²)	Maximum Power Consumption (W)	Diversity Factor	Radiant Fraction
STUDIO 4 General Lighting	General Lighting	☑	W/m²	0.000	-	-	12.000	-	1	0.45

Reference	Maximum Sensible Gain (W/m²)	Maximum Sensible Gain (W)	Maximum Sensible Gain (W/person)	Maximum Power Consumption (W/m²)	Maximum Power Consumption (W)	Diversity Factor	Radiant Fraction	Meter	Variation Profile
New General Lighting	0.000	-	-	12.000	-	1	0.45	Electricity: Meter 1	STUDIO 4 Annual Profile

The outside air supply system supplies the space with its maximum air flow rate, operated with a variation profile.

Table 6.6 Template of Auxiliary, Natural ventilation, and infiltration settings.

Auxiliary Ventilation

Reference	Type	Assigned to Templates?	Max Flow	Variation Profile	Adjacent Condition
STUDIO 4 Auxiliary Ventilation	Auxiliary Ventilation	☑	10.0000 l/s/person	STUDIO 4 Annual Profile	External Air

Auxiliary Ventilation

Reference	Type	Assigned to Templates?	Max Flow	Variation Profile	Adjacent Condition
STUDIO 4 Natural Ventilation	Natural Ventilation	☑	0.5000 ach	STUDIO 4 Annual Profile	External Air

Infiltration

Reference	Type	Assigned to Templates?	Max Flow	Variation Profile	Adjacent Condition
Infiltration	Infiltration	☐	0.2500 ach	on continuously	External Air
STUDIO 4 Infiltration	Infiltration	☑	0.5000 ach	STUDIO 4 Annual Profile	External Air

This project used an air supply of 10 l/s-person, which is the default value in the IES VE database for the schools, even though the combined ventilation air rate is required to be 8.5 l/s-person occupancy in all lecture halls of institutional facilities by (Hedrick et al., (2013). ASHRAE 62.1. In the thermal templates of the IES VE, the supply air rates for the design studios were set to the default value as indicated above. See Table 6.5. In each studio space, a mechanical auxiliary ventilation system was installed. An auxiliary ventilation system calculates the heating, cooling, and dehumidification needed to transform outdoor air to the desired supply condition. Table 6.6 shows the input profile of infiltration and air exchanges, reference to people, occupant density, and standard sensible gain per person in the building.

Table 6.7 Input profile for infiltrations and air exchanges in the building.

People

	Reference	Type	Assigned to Templates?	Input Mode	Maximum Sensible Gain (W/person)	Maximum Latent Gain (W/person)	Variation Profile	Occupancy Density (m^2/person)	Allow profile to saturate
☑	STUDIO 4 People	People	☑	m^2/person	90.000	60.000	STUDIO 4 Annual Profile	10.000	☑
☐	People	People	☐	m^2/person	90.000	60.000	on continuously	10.000	☑

6.4 Simulation of Building for Passive Cooling

The simulation was conducted by gradually adding each design change to the existing cases. These changes were made as indicated in Tables 6.4, 6.5, and 6.6 to ensure improvement options were fully exploited to allow the effects of the changes on cooling load, occupant comfort, and fabric gains to be determined. For instance, natural ventilation enabled heat to escape from the building interiors once the thermal mass had increased; this instance was demonstrated in Shanmugga & Kannamma, (2022), which argued that thermal comfort inside classrooms of institutional buildings depends on air temperature, relative humidity, wind velocity, building's position and orientation.

Night cooling was more effective when coupled with thermal mass because of the heat storage possibilities and was applied after changing the materials' u-values. In addition, infiltration was adjusted from the actual and natural states as the insulation of the building was improved. As the building became more airtight, the air rate changes per hour decreased. Finally, the windows were replaced with more energy-efficient ones, thus boosting the envelope performance. The last four optimizations made to the building model were all focused on shading, reducing the amount of incident radiation on the building, and the resulting solar gains.

6.4.1. Solar Radiation and Sun-cast Analysis of Building Form.

The amount of solar radiation that strikes a building can greatly impact its structure. Increasing insulation should be done thoughtfully in hot/dry climates, as high thermal mass structures cannot release heat efficiently. Taking advantage of a thermal lag effect, in which day-to-night temperature variations are greater than 10°C, the building should be well-shaded and facing the right direction.

Figure 6-5 (A and B) illustrates the amount of solar irradiation in terms of solar energy received by the building, and (B) illustrates the form based on exposure hours. The rooftop receives the highest energy (sunlight and heat) of 2156.19kWh/m2; other parts of the building receive the lowest energy of 4212.5kWh/m2 in a year. The building remains exposed to the sun's rays that pass directly overhead throughout the year; the simulation indicates a total solar exposure hour of 4289.99hrs as the highest and 429.00hrs as the lowest, and the roof receives over 30% more irradiation than any other façade illustrated in Figure 6-5 (A) Show solar energy analysis, this was saved because of its importance for future parametric analysis.

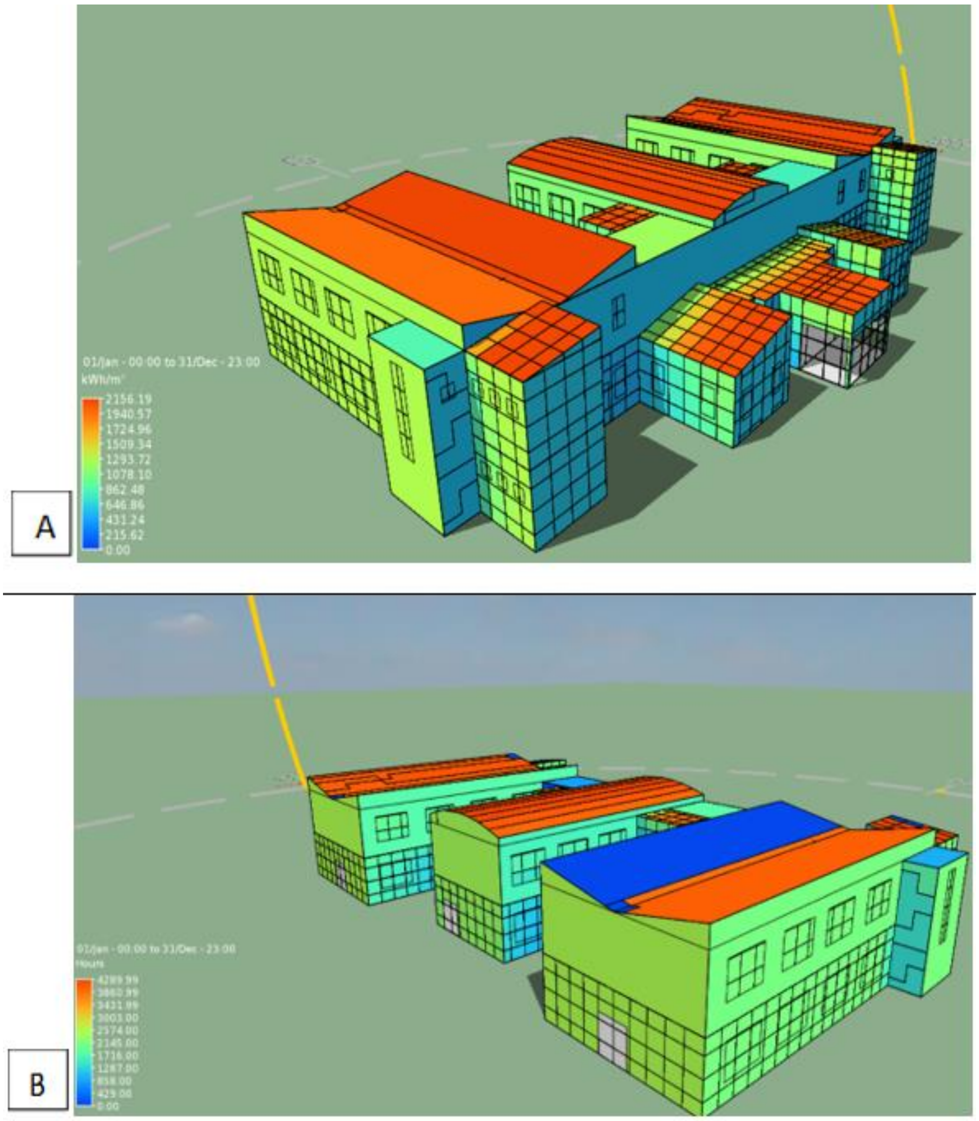

Figure 6-5 Yearly Relative minimum and maximum Solar Energy (kWh/m2) (A). Yearly Solar irradiation Exposure hours (B), incident on the building envelope.

6.4.2 Simulation of the Building Fabric External and Internal Heat Gains

The results of the simulation in Figures 6-6 and 6-7 illustrate the effect of different u-values on the internal and external conduction gains of a building. Internal conduction gains comprise of any sources of heat emanating within the interiors of structure, while external gains refer to the heat coming from outside sources, generally taken in by the building.

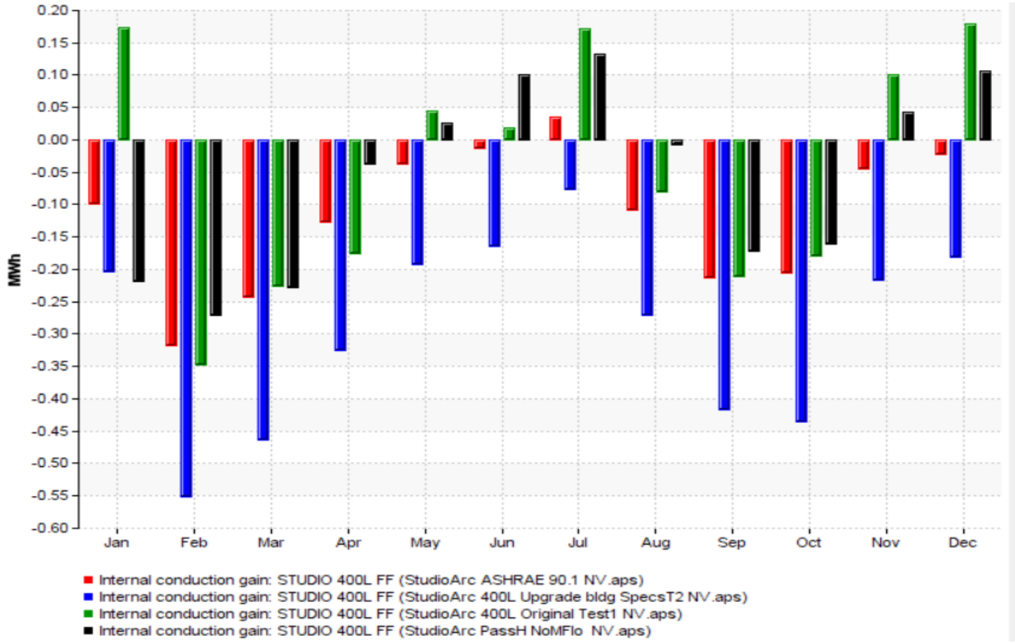

Figure 6-6 A comparison of internal conduction gains for each fabric test is shown in 400L Studio FF.

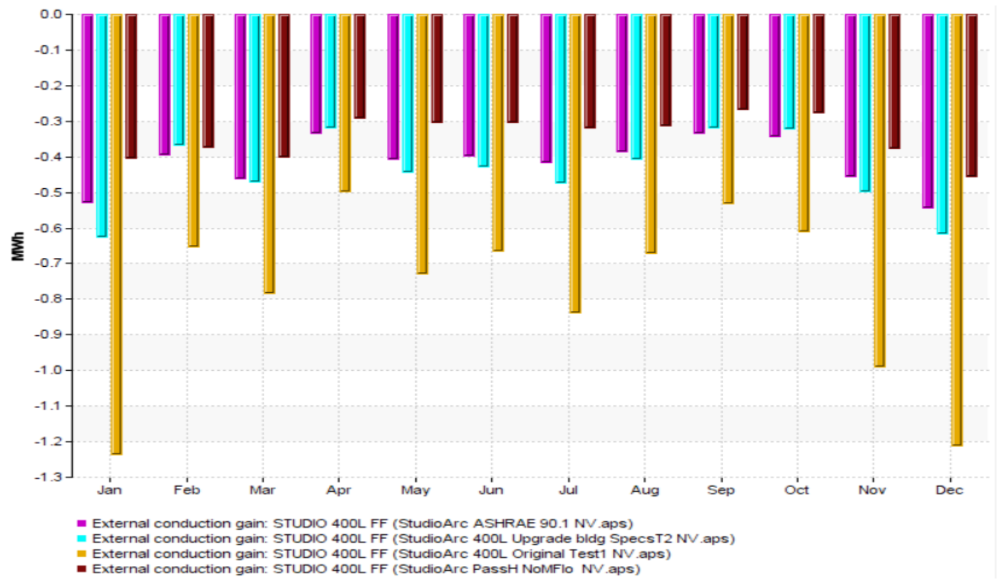

Figure 6-7 Comparison of external conduction gains for each fabric test, shown in 400L Studio FF.

The negative effect of external conduction gains represents heat loss to the environment, while positive internal conduction gains point to the construction taking in more heat through its interior surfaces. The results indicate that when the u-value is reduced, there is increased heat retention, which may not be beneficial.

I. *Fabric U-Value Simulation*

The fabric construction test in Figure 6-7 shows how the highest u-value means greater heat transmission coefficient. The chart explains why the overall fabric options have their external conduction gains change from positive to negative over the year, and this was because the fabric loses heat, meaning the rate of heat loss is greater than absorption. The "Passive House" design does not provide much passive cooling for the building than the fabric upgrade specification T2, which performs the best with the higher mean difference of -0.2041(MWh), with substantial negative internal conduction gains. The original fabric T1, has lower heat loss and higher conduction gains than other tests (as shown in Figure 6-7 and Table 6-2). The PassivHaus and ASHRAE 90.1 differences are -0.3879 and 0.4119, having simultaneous outcomes regarding their gains, while original T1 has the least performance difference of -1.0142MWh. The heat gained in the interior spaces of the building is positive, and the heat lost outside is usually negative (Figure 5.6). These two tests guide passive cooling fabric improvement for thermal comfort, as the heat losses have been regular over the years.

Fabric upgraded Test 2, which has its construction element lighter and enhanced, has the greatest heat performance through its materials than all the tests by a large margin (Figure 5.8). The original fabric T1 is a phenomenon attributable to the roof being exposed to the most solar radiation and fabric element with thermal energy storage due to its high thermal inertia against temperature changes. Since the dry bulb temperature remains constant throughout the day, the heat cannot be released, thus causing excessive gains. The external conduction gains in Figure 6-6 demonstrate that this test can remove the heat back into the environment. The thermal lag created by the roof retains the heat for a long period during the peak daytime temperature. However, convection air movement can draw the heat out of the high-mass fabric and transfer it into the surrounding environment, even when the diurnal temperature is low.

Table 6-8 displays the contrast between the internal and external conduction gains for each experiment presented in Figures 6-7 and 6-8. Each comparison is negative, implying more heat is lost than obtained. Consequently, all the fabric u-values tested are losing heat to the environment. To demonstrate the ideal characteristic fabrics with less heat release values are required for external gains and vice versa. Studio rooms with immediate roofs above 400L at first-floor (FF) levels studios will receive more solar radiation, necessitating a higher thermal transfer coefficient to counter it. Despite the high air temperatures and dry humidity levels throughout the day and night, lightweight and heavyweight construction combined with heat storage capabilities can still be used to reduce the cooling load during peak times, and the low thermal mass enables the heat to be expelled.

Table 6.8 Summary of fabric gains for each fabric test in '400L studio.'

S/No	Simul. Options	Annual mean internal conduction gain (MWh)	Annual mean external conduction gain (MWh)	Difference (MWh)
1	Upgraded Form T2	-0.3996	-0.6037	-0.2041
2	PassivHaus	-0.0783	-0.4662	-0.3879
3	ASHRAE 90.1	-0.1592	-0.5711	-0.4119
4	Original Form T1	-0.0606	-1.0748	-1.0142

To ensure thermal comfort is provided by the building, Figure 6-8 shows the level of occupants' comfort over the year for the analyzed T2 upgraded fabric specification and PassivHaus. When the outdoor air is hottest, the roof fabric's increased heat storage capacity helps keep the indoor air temperature from getting too high, keeping occupants' hotter. The optimization method met the PassivHaus specifications, having the most positive effect.

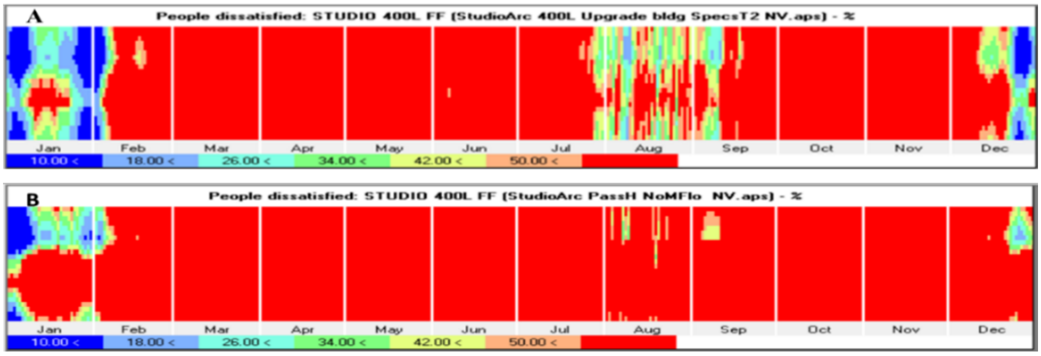

Figure 6-8 Comparison of dissatisfaction between the Upgraded fabric (A) and effective fabric test (B), in 400L studio due to temperature rise and discomfort.

The percentage of individuals who were not satisfied remained high from March to November, with an average of 89.45% compared with a decrease of 74.74% in the yearly average of unsatisfied individuals, a decline of 14.71%.

II. Fabric U-Value

Table 6.8 displays the different U-value specifications chosen for examination in this construction element.

Table 6.9 Fabric optimization of u-values with selected global Standard

Fabric U-Values (W/M2k)- Original PassivHaus ASHRAE 90.1 Variant 1 'Test								
Building Elements	**Original Fabric T1 Simulation**		**PassivHaus Simulation**		**ASHRAE 90.1 Simulation**		**Upgrade Test T2**	
	Regula	Actual	Regula	Actual	Regula	Actual	Regul	Actual
External Walls	1.43	1.426	≤ 0.15	0.153	0.85	0.852	1.43	1.436
Internal Partition	1.26	1.264	≤ 0.15	0.154	0.85	0.853	1.26	1.264
Roof	7.14	7.139	≤ 0.15	0.152	0.22	0.224	1.25	1.250
Floor/ Ceiling	1.91	4.042	≤ 0.15	0.152	0.61	0.613	1.91	1.912
Ground Fl	1.71	1.713	≤ 0.15	0.153	0.61	0.612	1.7	1.713
Window Glazing	5.17	5.174	≤ 0.80	0.82	2.27	2.271	2.9	2.877
Door	5.88	5.880	≤ 0.80	0.84	0.85	0.850	2.1	2.163

This selection incorporates completely decreased values and individual components to assess how the building reacts to thermal capacity and heat within the envelope. The values also include the actual values and the regulations they are based on, when applicable. These values were adjusted using the Building Template Manager in VE. Upgrade test T2 has less adjustment on glazing and roof values, and the PassivHaus, notable for its standard in performance, were selected and compared with the original test T1.

III. Simulation of building free cooling and night-time purging

The Apache building system involves utilizing natural ventilation to cool the interior during occupancy hours, and when the outside temperature is lower than the interior and can provide cooling benefits (generally in the evening), windows are opened to take advantage of it. At night, the heat gained throughout the day is released using the Apache system's "changeover mixed mode free cooling-natural ventilation" system.

6.4.3 Simulation of Natural Ventilation

The building's elements and their entries with natural air influx and outflux were considered when simulating the whole structure to determine the effect of ventilation. The analysis (including both windows and door frames) and the schedule of each element was set on natural ventilation mode. The doors and top-hung windows were given an openable proportion of 100% and a maximum opening angle of 30° throughout the building's operating hours.

i. Infiltration and air tightness

The air tightness of a building directly impacts the infiltration rate, and it is the only factor that can be optimized. If the thermal envelope is sealed tightly, the air is less likely to enter and exit the building. Other factors that contribute to the infiltration rate, such as wind speed and direction, orientation, and the temperature difference between the interior and exterior, remain constant (Touloupaki and Theodosiou, 2017). According to the (2021), institutional buildings are required not to leak to the higher air change rate of 50Pa, equivalent to 2.55h-1 as stated by Mohamed et al. (2021) CIBSE. To achieve this rate, the building was simulated by gradually reducing the initial infiltration rate of 0.5 ACH to 0.35 ACH, 0.3 ACH, 0.25 ACH, and 0.2 ACH. These changes were made using the 'divide by 20 rules of thumb' from Pasos et al. (2019), which suggests a minimum infiltration rate of 0.1275 ACH.

ii. Glazing values adjustment

Window glazing adjustment is effective in indoor lighting provision and regulations. G-values are used as a measure of the proportion of the sun's radiation that can go through a window. In places with hotter climates, a lower g-value is more desirable as a smaller amount of the sun's radiation can enter the building. The Studio complex has unique glazing characteristics that are common to the built campus infrastructure. To make these adjustments, the Building Template Manager was used to alter the glazing g-values and fabric u-values. Table 6.9 displays the various glazing choices that were tested.

Table 6.10 Window/Glazing specifications

Glazing Type	**U-Value (M/m2K)**		**G-Value**	**Cavity size between in (mm)**
	Suggested	**Actual**		
Single Glazing- Original	-	5.174	0.4823	-
Double glazing (Air filled)	2.9	2.877	0.3099	12
Tripple glazing (Air filled)	2.1	2.120	0,2205	12
Triple-glazing (Low-E, εn = 0.05, argon filled)	1.5	1.503	0.2461	16

6.4.4 Simulation of Building for Shading

A simulation applying green elements was carried out to demonstrate the impact of green shading on reducing internal solar gains. Structures such as hoods, awnings, horizontal louvres, and recesses erected over the windows also shade the buildings. However, the selection of shading elements in terms of materials should be with precision to those with lower thermal mass and conduction gains. (Trepci et al., 2021).

i. Shading device

Shading devices provide protection from direct protection solar radiation on the windows. Horizontal overhangs were created above all east and west-facing windows and specified as local shade in ModelIT. Multiple simulations were conducted to assess the advantages of the shading projections. The shading devices were projected away from the edge of the building between 0m and 1m in 0.5m intervals, as shown in Figure 6-9. The IESVE software was then used with the FlucsDL feature to analyse the daylight entering the spaces and the VistaPro feature to compare it to the solar gains. The most appropriate shading type and size were identified as they both minimized solar gains and allowed for adequate natural light.

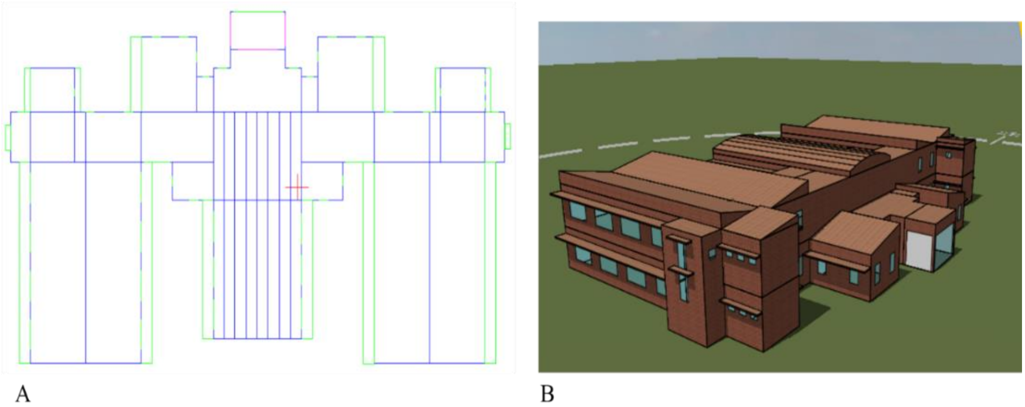

Figure 6-9 Shading projections in (A) Plan (green colour) and (B) in Perspective view.

ii. *Vegetation shading*

The IESVE software's component modeler was used to download several trees from an online library and add them to the model with ModelIT.

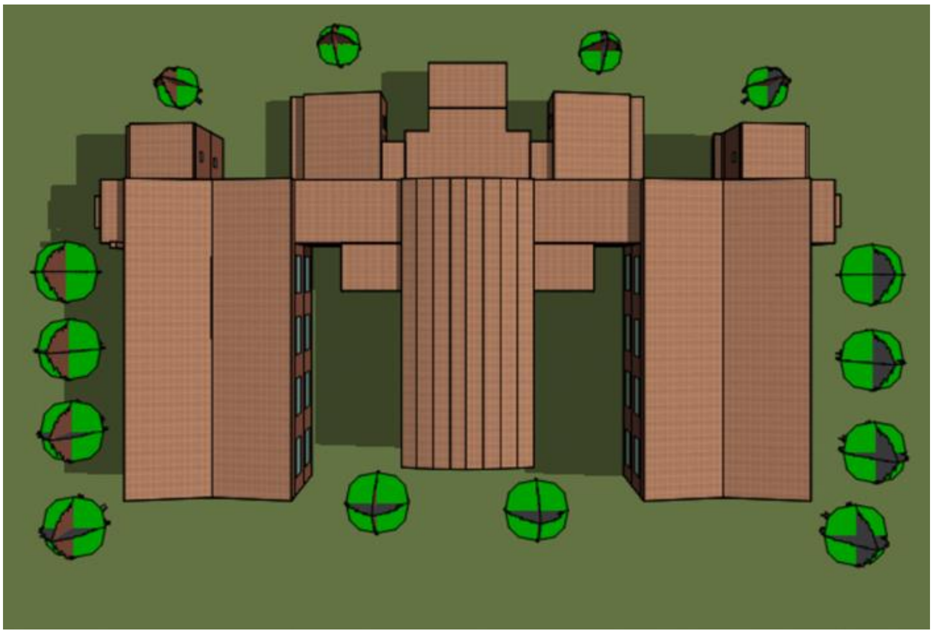

Figure 6-10 Vegetation placement around the building.

Figure 6-10 displays the chosen vegetation type, which is 9 meters tall and 5.5 meters wide. There are 4 on the south and north facades of the building, with 4 smaller (6 meters high) placed at the approach view and 2-trees at the rear. SunCast and Apache were used to model the shading effect of the trees only. Much research has recommended the efficiency of using natural vegetation, such as large trees, to provide shade in building envelope; trees with good foliage significantly contribute to air filtration. (Trepci et al., 2021; Mahmoud & Abdallah, 2022; and Abdallah, 2022).

iii. *Roof shading (canopy)*

The canopy, which provides roof shading, is designed, and crafted from solid Aluminium panels (as seen in Figure 6-11) and is projected 1.2 meters above the roof at its highest point. Utilizing ModelIT, the design alteration was defined as a 'local shade' to exclude it from heat gain/load calculations. Furthermore, the canopy will serve as a foundation on which photovoltaic panels can be mounted for renewable energy sources.

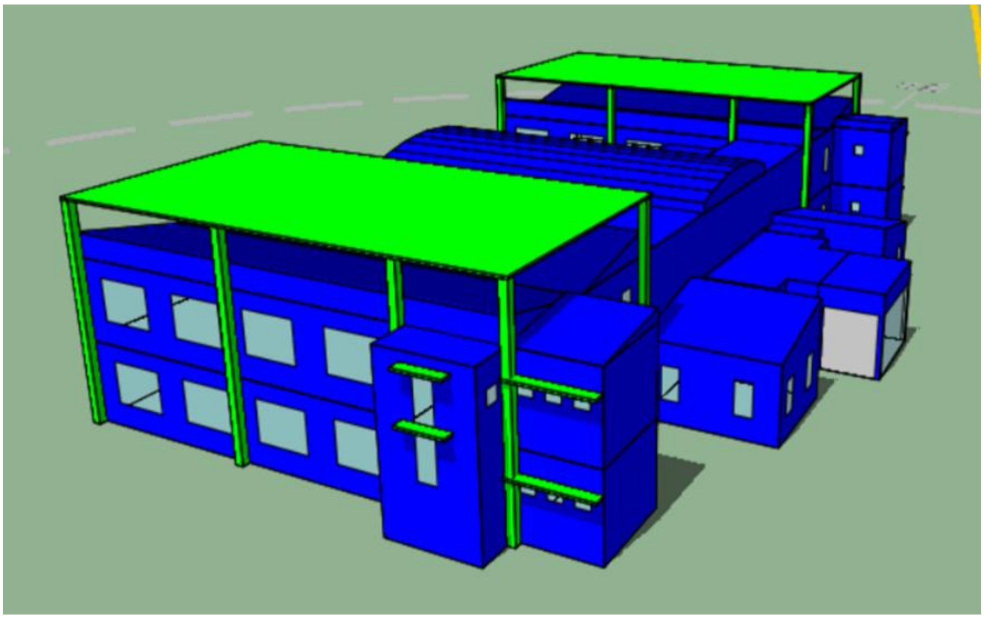

Figure 6-11 Projected roof canopy shade (green); system design using IESVE ModelIT.

Table 6.10 shows the aluminium roof deck specification with reduced conductivity to the recommended fabric standard.

Table 6.11 Roof shade; Aluminium deck inputted construction template

Surfaces | Regulations | RadianceIES

Outside
Emissivity: 0.900 — Resistance (m²K/W): 0.1000 — ☑ Default
Solar Absorptance: 0.700

Inside
Emissivity: 0.900 — Resistance (m²K/W): 0.1000 — ☑ Default
Solar Absorptance: 0.550

Construction Layers (Outside To Inside) — System Materials... — Project Materials..

Material	Thickness mm	Conductivity W/(m·K)	Density kg/m³	Specific Heat Capacity J/(kg·K)	Resistance m²K/W	Vapour Resistivity GN·s/(kg·m)	Category
[ALM] ALUMINIUM	30.0	0.0500	2800.0	896.0	0.6000	3000000.000	Metals

iv. Solar panel shading

ModelIT was used to fit photovoltaic panels to the roof canopy, covering 160.37m^2 surface, each with 72 Monocrystalline Silicon PV cells. As illustrated in Figure 6-12, this results in view of the solar PV panel setup on the top-level shade, each panel measuring 2 x 1.5 meters.

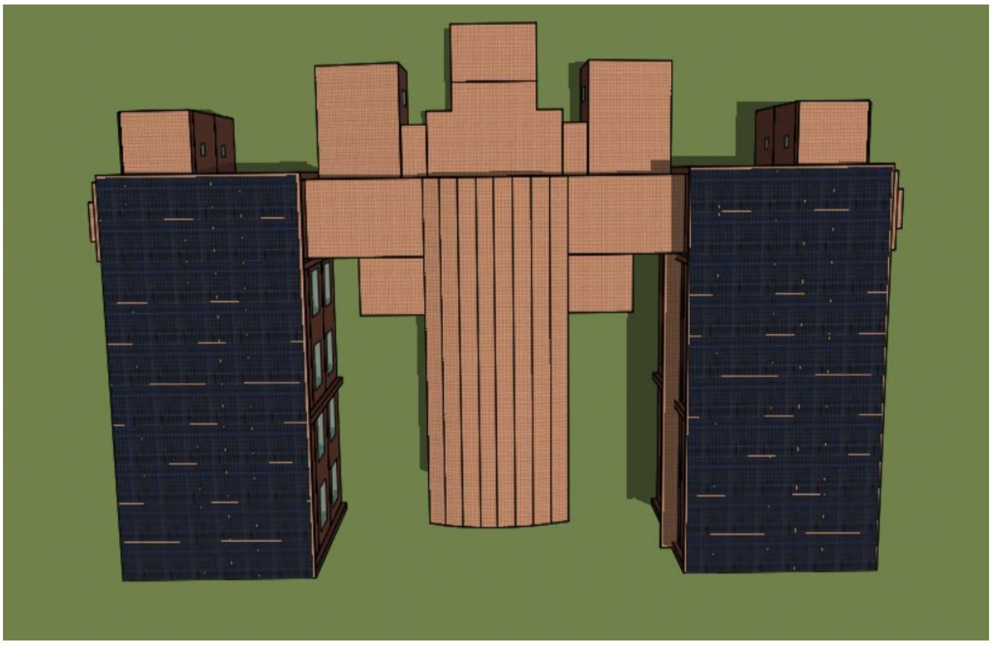

Figure 6-12 Solar panel layout and arrangement on the roof canopy..

6.4.5 Model Validation Process

The IES simulated model validation process was initiated by comparing the results of air temperatures from the simulated model with the measure indices of the data logging device (NETATMO). Although the experimental process was for a year, it began on 1st January 2021 and continued until 31st December 2021 hourly weeklong data was recorded by the device and simulation reading was used to calculate the difference between the two recorded air temperatures based on the formula (Corrado & Fabrizio, 2019).

$$MBE = \frac{\sum_{period}(S-M)_{Interval}}{\sum_{Period} M_{Interval}} * \ 100\%. \qquad (6.1)$$

Where *M* is the measured energy data point during the time interval and *S* is the simulated energy data point during the same time interval. The *CvRMSE* is computed through the following formulas:

$$Cv(RMSE_{Period}) = \frac{RMSE_{Period}}{A_{Period}} \times 100 \qquad (6.2)$$

$$RMSE_{Period} = \sqrt{\frac{\sum (S-M)^2_{Interval}}{N_{Interval}}} \qquad (6.3)$$

Where $N_{Interval}$ is the number of time intervals considered for the monitored period.

6.5 Parametric (Simulation) Results and Analysis

The energy simulation software was applied to the case study building to evaluate the thermal performance and solar analysis when applying various passive cooling strategies discussed in the second chapter. Each simulation was performed over one year, and the results were presented for the most sweltering week of the year (from the 10th to the 17th of April in the hot summer season) is the hottest week and the hottest day (Tuesday 11th of April).

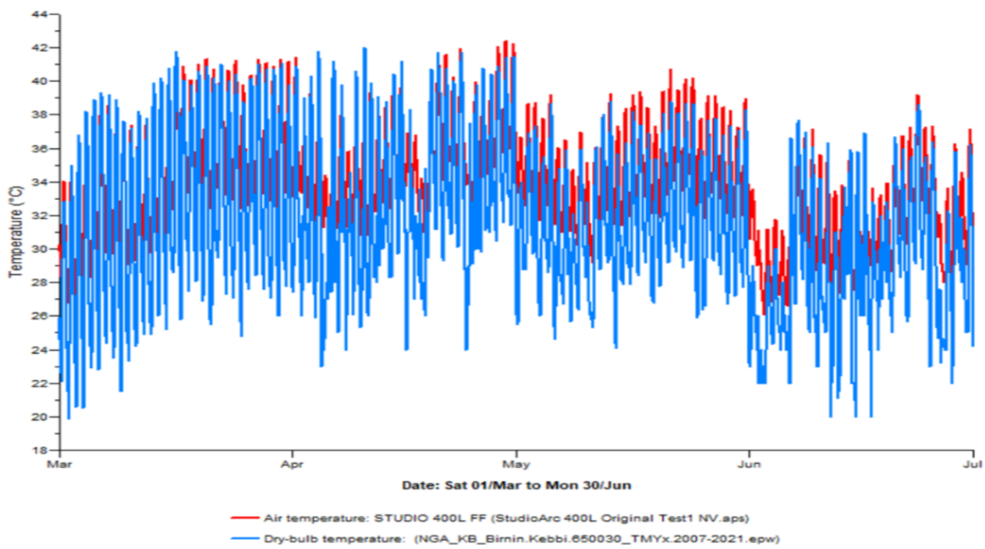

Figure 6-13 Comparison of external and internal temperature, in 400L Arch. Studio (original fabric) during Hot weather.

For comparison, the temperatures and humidity of the week of the 10th to the 17th of January 2021 (in the cold/dry winter season) were also considered for the thermal analysis of 400Level Studio on the First Floor (FF), chosen because it is the most frequently occupied by students throughout the building and has enough glazing to illustrate the gains accurately. Figures 6-13 and 6-14 compare the inside and outside temperatures of the chosen area over the entire year and for the week. The Arch. Studio IES-VE Model. The report is attached as Appendix VI.

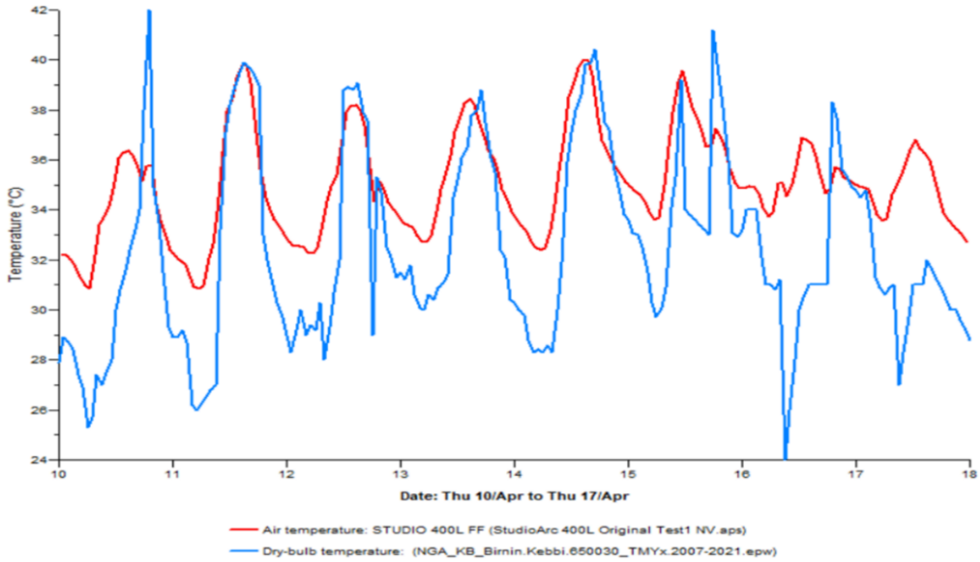

Figure 6-14 Comparison of external and internal temperature in Arch. Studio, in the hottest week of April.

6.5.1 Simulation Results and Analysis of Passive Cooling Strategies

6.5.2 Natural ventilation

Figure 6-15 illustrates how natural ventilation affects the air temperature in the studio. The results demonstrate a gap of 1.5°C between the minimum room temperatures and in the average temperature. Olatunji Jimoh & Umar (2021), natural ventilation influences interior temperatures even when the optimum temperature of the indoor learning spaces was not achieved.

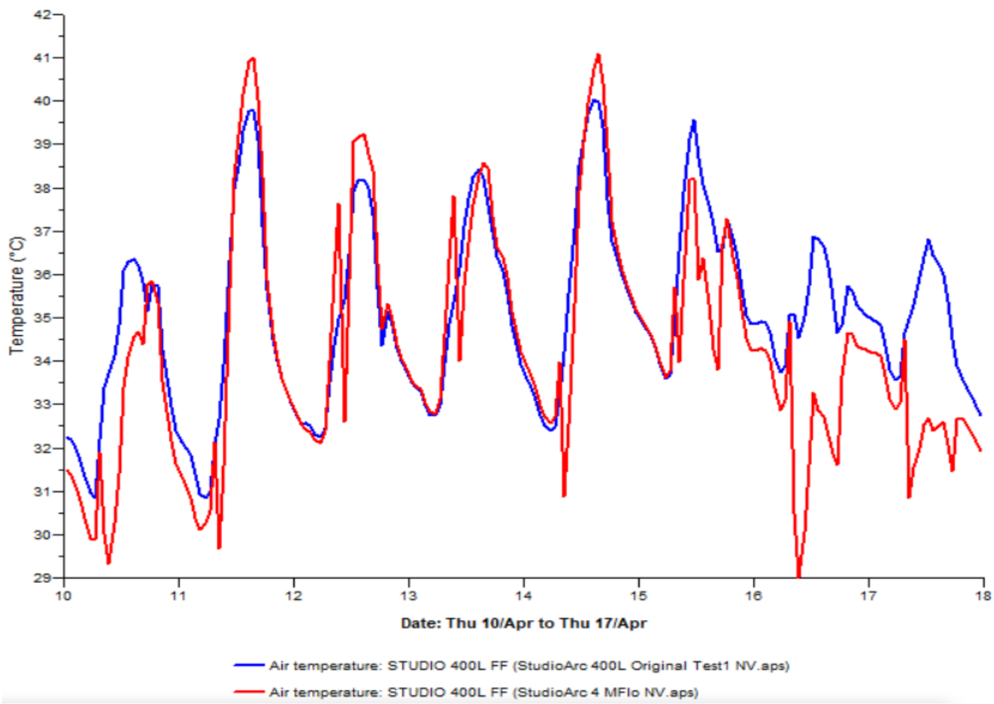

Figure 6-15 Comparison of indoor air temperature with and without natural ventilation.

When comparing Figures 6-8, which displays the number of unsatisfied indices of occupants when natural ventilation is not sufficient, the drastic change is seen from 9 a.m. to throughout the night. This could be because of increased air temperature, carbon dioxide levels, and low humidity in the interiors.

The findings of satisfaction and corresponding dissatisfaction in Figure 6-16 indicates insufficiency of natural ventilation and heat built-up in the studio this verifies that natural ventilation can foster excellent interior air quality, improve inhabitants' thermal contentment, and elevate the inhabitants' thermal wellbeing. By opening the building's windows, improved air motion from outside air flows can eliminate the heat that has built up in the building, which is displayed in the graph as lower indoor air temperatures. This consequently decreases the need for mechanical cooling as the interior temperatures are closer to the agreeable temperatures and require less cooling energy to reach the desired comfort.

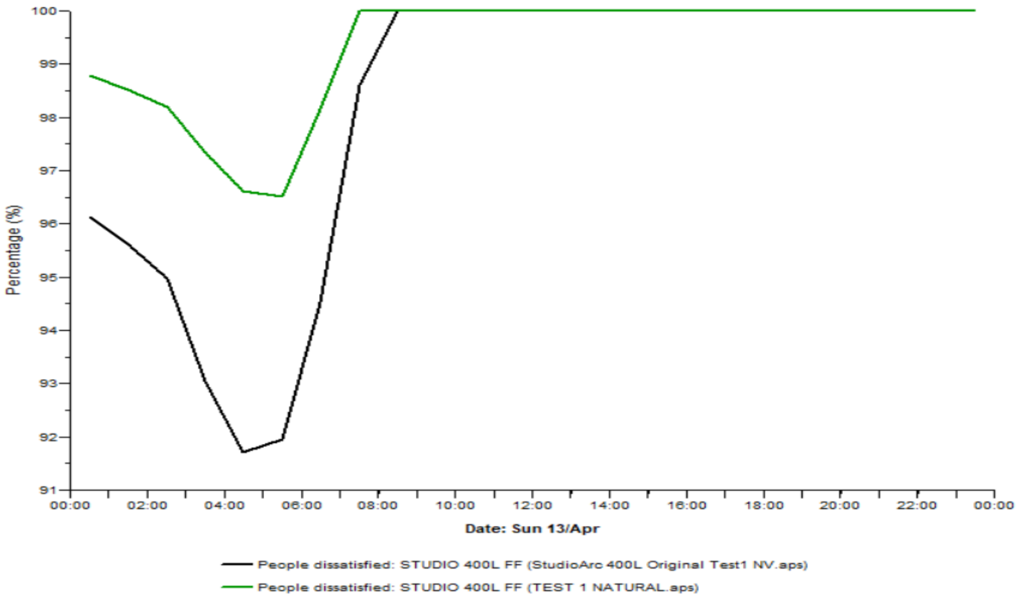

Figure 6-16 Comparison of occupant satisfaction with and without natural ventilation, in 400L Arch Studio.

6.5.3 Building Gains

Free cooling is when the external temperature is lower than the internal temperature; there is the potential for free cooling to occur, usually in the evenings when there is no solar radiation; this can be achieved with a mechanical ventilation system or through natural ventilation. Natural ventilation is a passive approach which does not require any energy consumption. A convective exchange between the cool, fresh air and the building's fabric can occur if the outdoor air flow rate is sufficient. However, the table suggests that introducing natural, free cooling only increases the mean annual air temperature regardless of the fabric. The number of people dissatisfied with the air temperature is directly related to the indoor temperature.

6.5.4 Free Cooling and Night-Time Purge

High thermal mass materials are most effective when used in conjunction with night cooling, as they allow the heat stored during the day to be released by creating air movement. The original building specifications Test 1, ASHRAE-90.1, PassivHaus, and the upgraded building ‘Test 2’ were tested. Tables 6-11 and 6-12 display the effect of night cooling in both the 'hot' and 'cold/dry' months. The greatest impact of natural, free cooling is seen with the PassivHaus specifications, as it not only has a positive effect during the hottest month but the mean annual temperature can be reduced to 3.5°C, based on the comparison in Table 6.11, 10th-17th of the April month. Despite this, indoor air temperature in PassivHaus remains greater, 338.49°C high and 34.95°C low, than the other tests as the day-to-night temperature difference and night-time air velocity significantly affect the heat regulation.

Table 6.12 Comparison of mean air temperature and mean people dissatisfied in wet season.

Cooling Test 10th -17th April (Hottest Week of the Year)		
Building Fabric Test	**Mean Air Temperature (°C)**	**Mean People Dissatisfied (%)**
Original Building Specification	34.93	96.58
Original Building Specification (Natural free cooling)	33.76	91.98
Test 2 Building Specification	35.84	99.70
Test 2 Building Specification (Natural free cooling)	34.50	96.32
PassivHaus Specification	38.49	100.00
PassivHaus Specification (Natural free cooling)	34.95	95.96

Using natural, free cooling in PassivHaus is an effective solution. Statistics show that the mean air temperature was reduced by 1.2°C while the number of people who were least dissatisfied was reduced during the month of January. The upgraded building Test 2 has 0.1°C, meaning less air temperature reduction.

Table 6.13 Comparison of mean air temperature and mean people dissatisfied with the night cooling test during the dry season.

Cooling Test 2nd -9th January (Coldest Week of the Year)		
Building Fabric Test	**Mean Air Temperature (°C)**	**Mean People Dissatisfied (%)**
Original Building Specification T1	26.49	77.48
Original Building Specification (Natural free cooling)	26.66	83.43
Test 2 Building Specification	28.14	55.91
Test 2 Building Specification (Natural free cooling)	28.04	87.43
PassivHaus Specification	29.29	99.03
PassivHaus Specification (Natural free cooling)	28.07	97.21

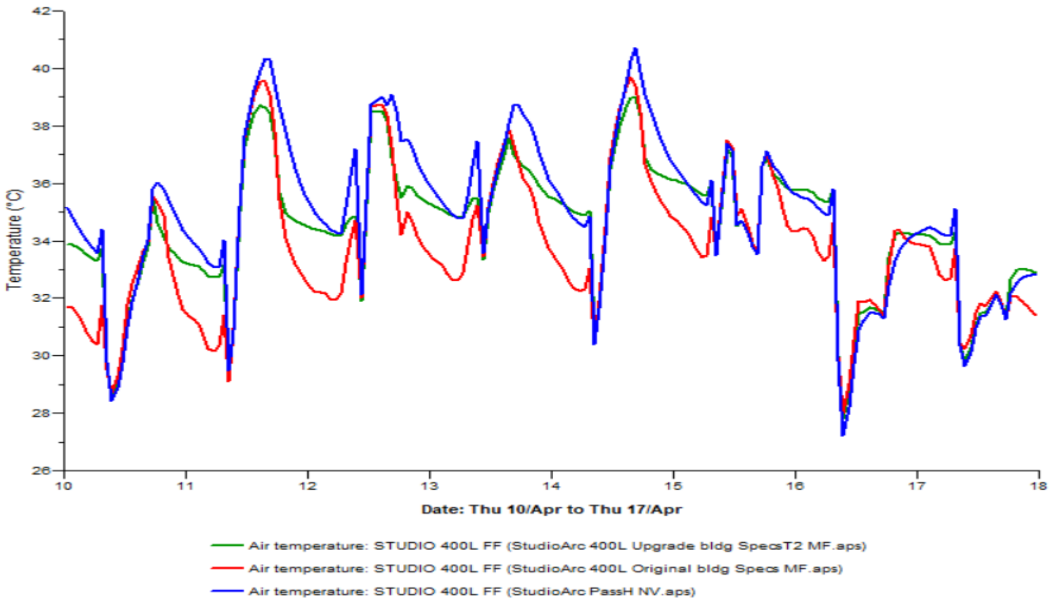

Figure 6-17 Comparison of air temperature for each night cooling test in 400L Studio during the hot season.

Figures 6-17 and 6-18 demonstrate that in the original building specification (Test 1) with natural, free cooling injection, the temperature rose from 26.49-26.66ºC. People are more comfortable when the air temperature is lower.

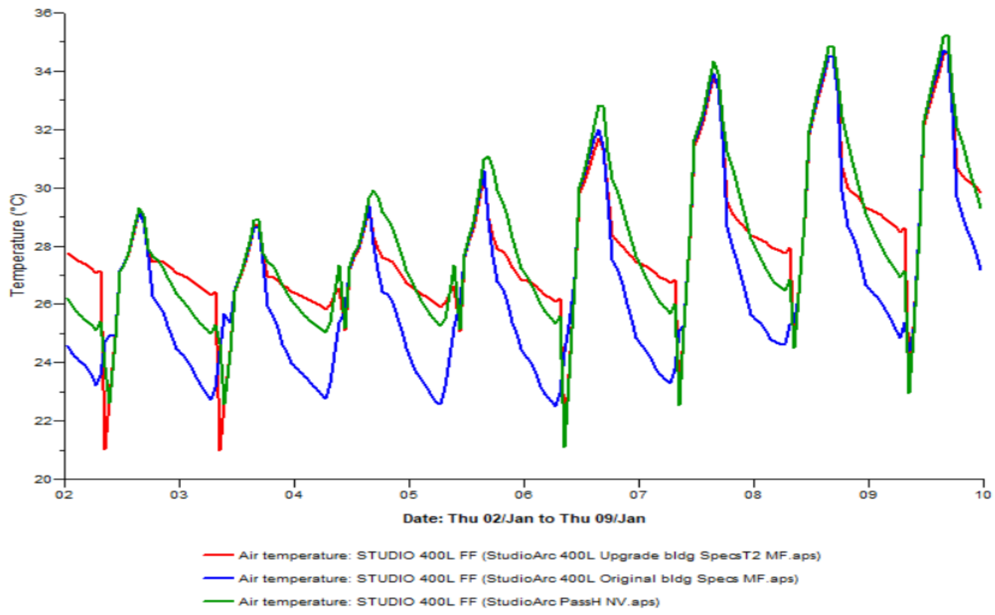

Figure 6-18 Comparison of air temperature for each night cooling test in 400L Studio during the cold dry season.

6.5.5 Infiltration and air tightness

The graph in Figure 6-19 illustrates how the infiltration rate through the 400L studio alters when the amount of air changes per hour is modified. Generally, infiltration is thought of as unintentional and undesirable. However, in this case, allowing more drafts to enter the building can decrease the cooling load. Initially, the building had a rate of 0.5 ACH, which can be lowered by making the structure airtight.

It also demonstrates that infiltration results in net heat loss, making it impossible to use infiltration to regulate thermal comfort within the building during operating hours. As the infiltration rate decreases, the potential to use infiltration as a heat source diminishes. Consequently, the indoor air temperature will rise due to the other internal gains, as the air is not being replaced sufficiently.

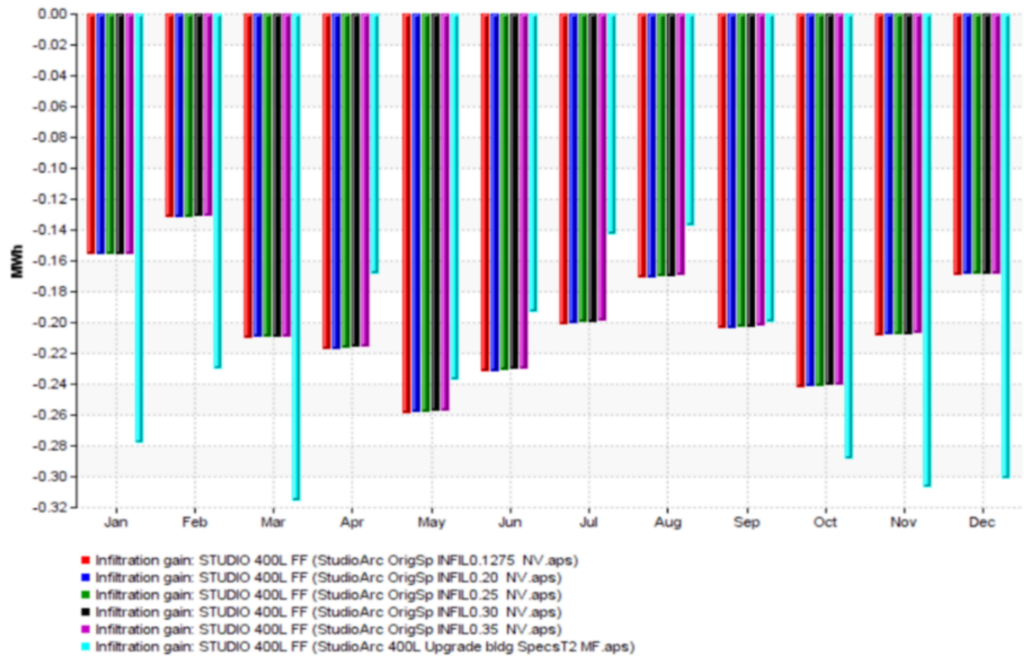

Figure 6-19 Comparison of infiltration gain for infiltration test in the studio.

Figure 6-19 shows that the upgraded T2 test fabric (0.5 ACH) has the best infiltration rate, resulting in a 14.8% greater infiltration loss than the 0.35 ACH. Building interiors located in hot/dry climatic regions have an increased rate of infiltration, which is associated with outdoor heat entering the building. Since the difference between indoor and outdoor temperatures is small, the air temperature inside is not affected much. Table 6.13 shows the maximum and minimum temperature differences between 21.5 and 20.4 °C in the test ranges.

Table 6.14 Input data: Mean annual air temperature for each infiltration test in 400L Studio FF.

Variable	LOC	File Name	Min val.	Time	Max val.	Max time	Mean
Air temp	Stud 400L	Infil. 0.1275	22.14	06:30/27/Dec	42.49	15:30/29/April	31.32
Air temp	Stud 400L	Infil. 0.20	22.14	06:30/27/Dec	42.48	15:30/29/April	31.31
Air temp	Stud 400L	Infil. 0.25	22.14	06:30/27/Dec	42.47	15:30/29/April	31.31
Air temp	Stud 400L	Infil. 0.30	22.14	06:30/27/Dec	42.46	15:30/29/April	31.30
Air temp	Stud 400L	Infil. 0.35	22.14	06:30/27/Dec	42.45	15:30/29/April	31.30
Air temp	Stud 400L	T2 bldg.0.5	19.78	08:30/23/Dec	41.23	15:30/16/March	31.72

The increased air changes are only beneficial in providing fresh air and improving air quality, but this can affect the indoor temperature. Infiltration is not a fix value it is pressed by buoyancy and wind forces, Table 6.14 illustrates.

Table 6.15 Infiltration rate for each infiltration test in 400L Studio FF

Var. Name	Location	Filename	Type	Min. Val.	Min. Time	Max. Val.	Max. Time	Mean
Infiltration	STUDIO	StudioArc OrigSp INFIL0.1275	Gain (kW)	-1.2513	07:30,24/Apr	0.8115	09:30,10/Sep	-0.2734
Infiltration	STUDIO	StudioArc OrigSp INFIL0.20	Gain (kW)	-1.2509	07:30,24/Apr	0.8118	09:30,10/Sep	-0.2728
Infiltration	STUDIO	StudioArc OrigSp INFIL0.25	Gain (kW)	-1.2506	07:30,24/Apr	0.8120	09:30,10/Sep	-0.2724
Infiltration	STUDIO	StudioArc OrigSp INFIL0.30	Gain (kW)	-1.2504	07:30,24/Apr	0.8122	09:30,10/Sep	-0.2720
Infiltration	STUDIO	StudioArc OrigSp INFIL0.35	Gain (kW)	-1.2501	07:30,24/Apr	0.8124	09:30,10/Sep	-0.2716
Infiltration	STUDIO	StudioArc 400L Upgrade bldg	Gain (kW)	-1.4714	07:30,24/Apr	0.7568	19:30,06/Jun	-0.3189

Figure 6-20 illustrates a consistent result of CO_2 within range. The correlation between the concentration of CO_2 and infiltration rate in educational buildings was provided as a guide concerned with the need to decrease the CO_2 concentration in indoor learning spaces, ASHRAE-62, (2022) states that an average of less than 1500 ppm of CO2 concentration should be maintained during occupancy hours in a naturally ventilated teaching space. Keeping the CO2 concentration between 600 ppm and 1000 ppm is considered safe and within the acceptable range. All the building infiltration rates tested have met the suggested values.

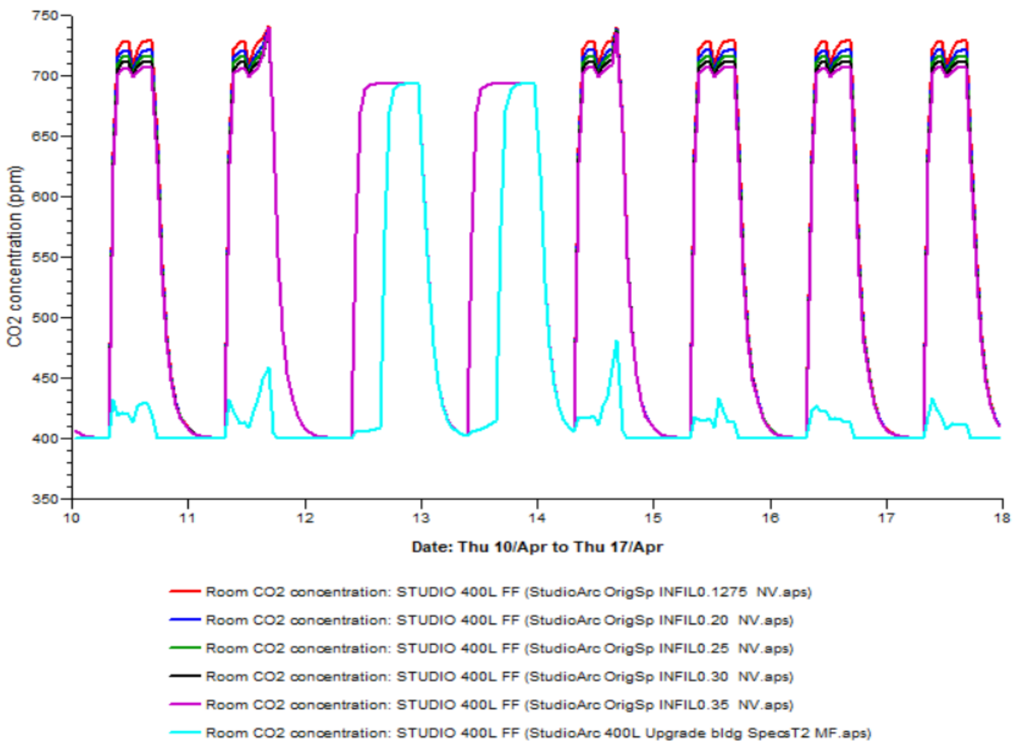

Figure 6-20 A comparison of room CO2 concentration for each infiltration test is shown in '400L Studio FF.

Table 6.16 Infiltration rate; varied test with People dissatisfied, 400L Studio FF

Var. Name	Location	Filename	Type	Min. Val.	Min. Time	Max. Val.	Max. Time	Mean
People dissati:	STUDIO 400L	StudioArc OrigSp INFIL0.1275 N	Percentage (%)	49.51	06:30,10/Apr	100.00	10:30,10/Apr	95.79
People dissati:	STUDIO 400L	StudioArc OrigSp INFIL0.20 NV.	Percentage (%)	49.41	06:30,10/Apr	100.00	10:30,10/Apr	95.77
People dissati:	STUDIO 400L	StudioArc OrigSp INFIL0.25 NV.	Percentage (%)	49.34	06:30,10/Apr	100.00	10:30,10/Apr	95.76
People dissati:	STUDIO 400L	StudioArc OrigSp INFIL0.30 NV.	Percentage (%)	49.27	06:30,10/Apr	100.00	10:30,10/Apr	95.75
People dissati:	STUDIO 400L	StudioArc OrigSp INFIL0.35 NV.	Percentage (%)	49.20	06:30,10/Apr	100.00	10:30,10/Apr	95.73
People dissati:	STUDIO 400L	StudioArc 400L Upgrade bldg Sp	Percentage (%)	60.93	09:30,16/Apr	100.00	17:30,10/Apr	96.32

Figure 6-21 demonstrates the influence of different infiltration rates on the number of dissatisfied occupants. The lowest CO2 concentration and highest infiltration rate was found to be 0.5 ACH, upgraded fabric T2 test specification with 96.3% which produced the most comfortable occupants. While increasing the air tightness of the building had a limited effect on occupant comfort, there was a reduction of about 0.6% in dissatisfied occupants' mean PPD (Table 6.15) and a decrease of 1.4°C in the mean annual air temperature when the air changes decreased at 0.35 ACH, see. Therefore, to optimize the model, this test will be enforced as it had a more positive effect on the indoor temperature than on the CO_2 concentration and the percentage of people dissatisfied.

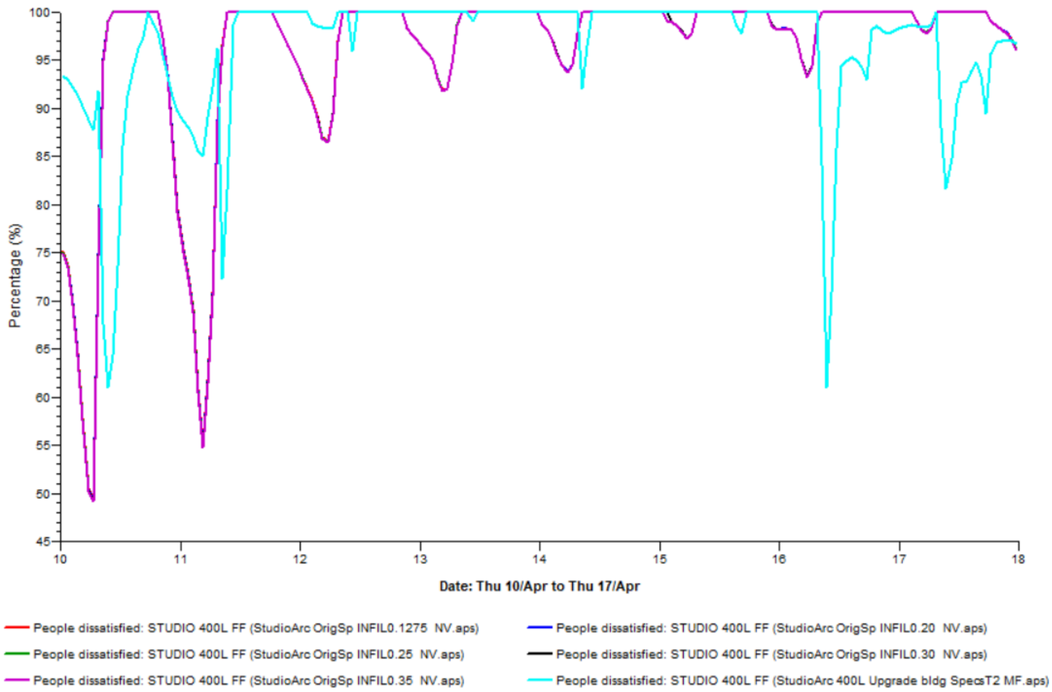

Figure 6-21 Comparison of people dissatisfied with each infiltration test in studio.

6.5.6 Glazing Adjustment.

In Figure 6-22 and Table 6.16, the effect of introducing insulation to the windows of the studio hall, which has many windows, is shown. In contrast to the increase in thermal mass that caused undesirable heat retention, the double and triple glazing did not have this effect. As the figure illustrates, the entire glazing types simulated demonstrate uniform characteristics and are successful at lowering the minimum temperature from 6:30 am to 2:30 pm; this helps to pre-cool the room, making it comfortable for people when they arrive.

Table 6.17 Infiltration rate; varied test with People dissatisfied, 400L Studio FF

Var. Name	Location	Filename	Type	Min. Val.	Min. Time	Max. Val.	Max. Time	Mean
Air temperatu	STUDIO 400	StudioArc TrippGlaz ArgonF2.0 NV	Temperature (°C)	30.89	06:30,10/Apr	40.05	14:30,14/Apr	35.09
Air temperatu	STUDIO 400	StudioArc TrippGlaz AirF2.1 NV.ap	Temperature (°C)	30.89	06:30,10/Apr	40.05	14:30,14/Apr	35.09
Air temperatu	STUDIO 400	StudioArc DoubGlaz AirF2.8 NV.a	Temperature (°C)	30.89	06:30,10/Apr	40.05	14:30,14/Apr	35.09
Air temperatu	STUDIO 400	StudioArc OrigSp INFIL0.35 NV.ap	Temperature (°C)	30.87	05:30,11/Apr	40.03	14:30,14/Apr	35.06

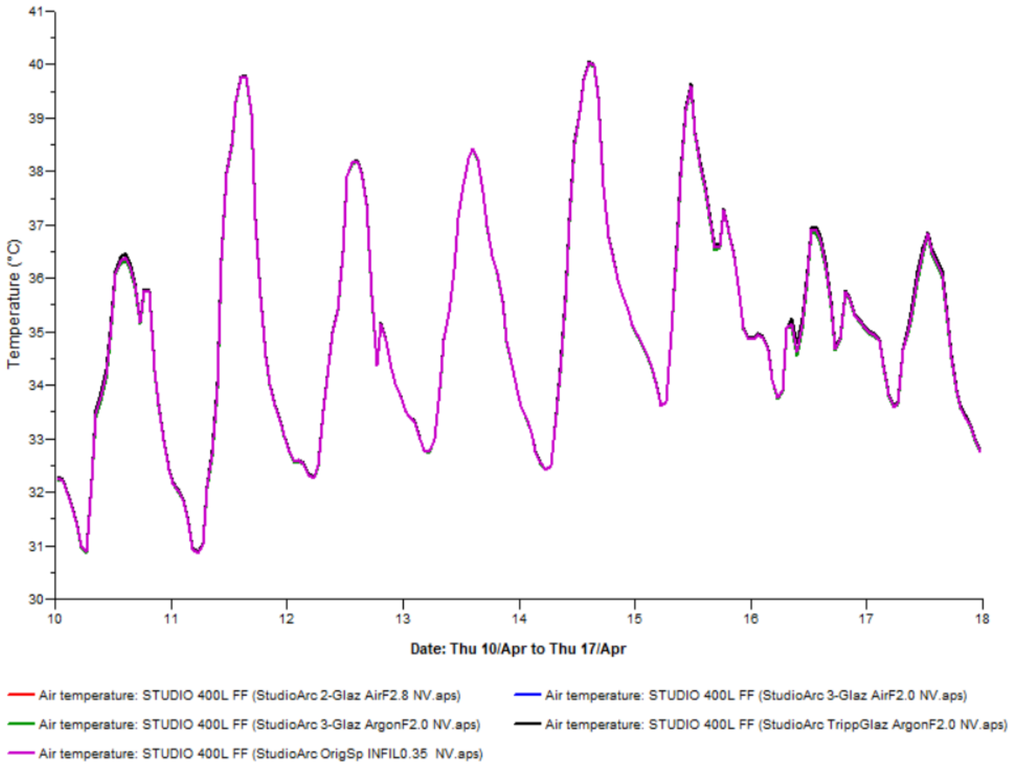

Figure 6-22 Comparison of air temperature for different glazing tests.

The diagram in Figure 6-23 illustrates how the solar gain remained constant when air-filled double glazing is simulated against building specification with infiltration 0.50ACH and 0.35ACH.

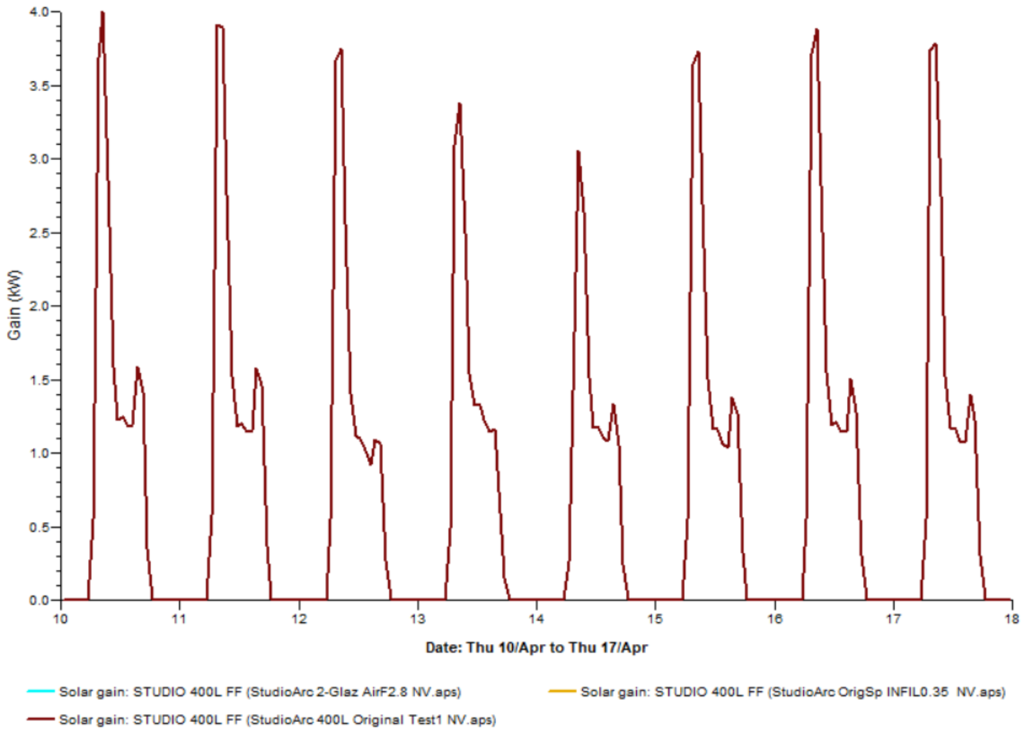

Figure 6-23 Comparison of solar gains between most effective glazing.

During the week studied, the solar gain was uniform and efficient in control from 00:30 am minimum. The optimization resulted in no annual solar gain reduction arising from the result. Change in glazing types has uniform effect on cooling demand. The result shows a uniform value regardless of the type of glazing used in the taste, this is attributed to the climatic zone (hot/dry). Although double glazing is an insulation layer that blocks conductive heat transfer and keeps the space cooler during the hottest months, but the simulation in Figure 6-23 proved no changes in terms mean air temperature and solar gain the values in the hottest week of April, remained constant at 35.09°C and 0.80KW. But if the insulation is increased to excessive thermal mass, heat is absorbed and trapped within the building, resulting in no further benefit.

6.5.7 Shading projections and daylight effect

The SunCast diagrams in Figure 6-24 indicate that the building's East and West facades receive the same solar radiation due to the sun's path at a 63º degree altitude over summer (A) and winter (B) periods of the year. This means a horizontal overhead shading device can be implemented to protect the windows.

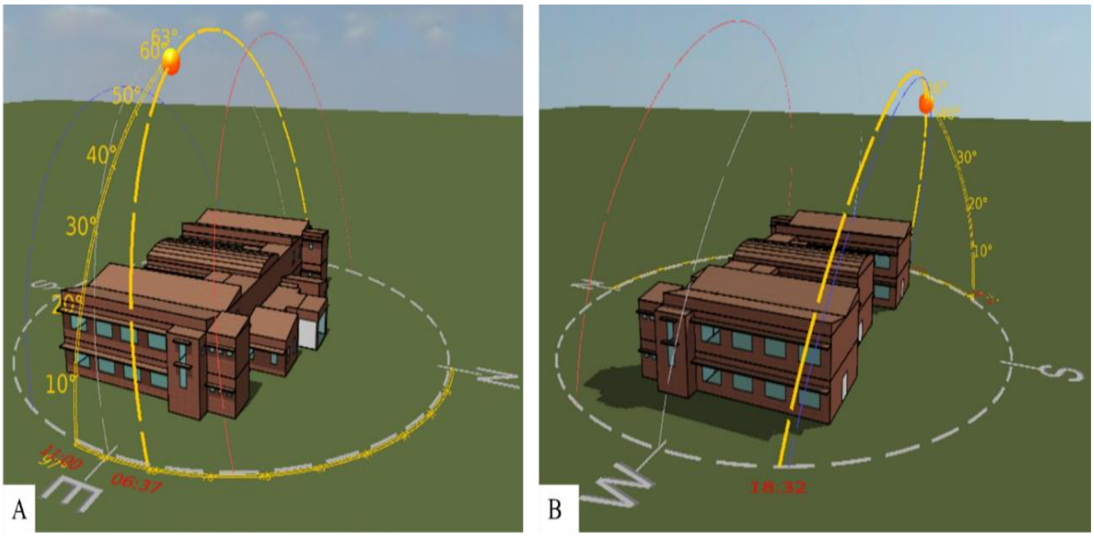

Figure 6-24 SunCast diagrams of the shaded building: (A) Hot season and (B) Cold season at 11:00am time.

Occupant satisfaction and energy efficiency are ensured if the indoor space remains bright and daylit, as artificial lighting creates internal gains that add to the cooling load. Natural daylighting is thus of utmost importance. Table 6.17 demonstrates the effect of shading on the daylight factor in Studio interiors, with the percentage of daylight above the 562-lux daylight threshold, slightly decreasing with the extension of shading length.

From Table 6.17 the daylight factor was stable at 4.6% across the 3-simulations in the studio. The minimum daylight factor for a classroom learning environment is 2% and 5% maximum. A 300-500 lux of illuminance was recommended by standards for reading and learning to maintain performance and efficiency (Yunitsyna and Toska, 2023, Rahman et al, 2019).

Table 6.18 Effect of shading projections on lighting

Test Iteration	(%) Daylight above threshold	(%) Daylight factor. Area-weighted average	Illuminance (Lux) Area-weighted average
-No shading	100.0	4.6	562.822
-0.5m Shading projections	100.0	4.6	562.822
-1m shading projection	99.9	4.6	562.522

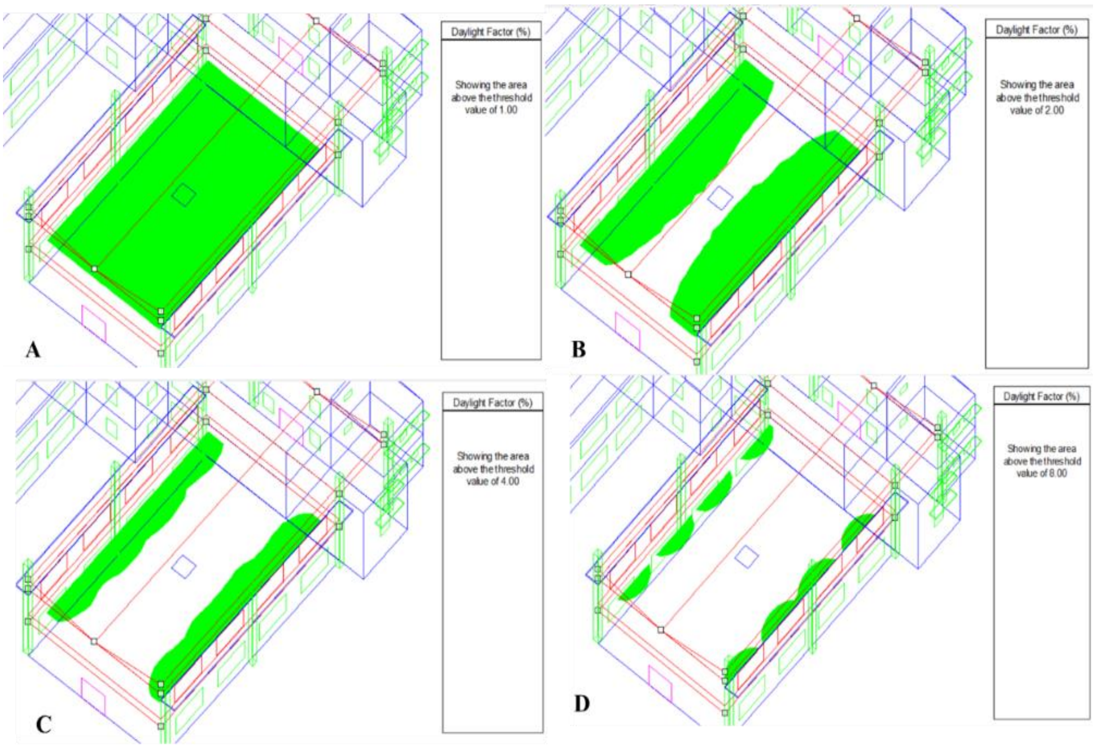

Figure 6-25 Effect of Daylight Factors in studios from 1, 2, 4 and 8% A, B, C and D, shown in 400L studio.

The result, as illustrated in Figure 6-25, shows the studio is well-lit and is within the recommended daylight factor. It is essential to select appropriate shading material since it will affect the amount of solar radiation absorbed, transmitted, and reflected. The local shade selection made on ModelIT will not include the effect of window projection material in energy calculation. The air temperature for different shading tests is presented in Figure 6-26, and it was seen that the maximum air temperature was reduced by 0.05°C (35.09 to 35.04ºC) from the week-long simulation by adding a meter of overhead shading. This effect was observed for both the minimum and maximum temperatures, showing that the material chosen for the overhead shading had a positive, albeit slight, impact on the building by redirecting radiation away from the building fabric. Across the year windows shading projections on 400L studio will have a mean saving of 0.03°C, more impactful at the maximum time of 15:30 in April.

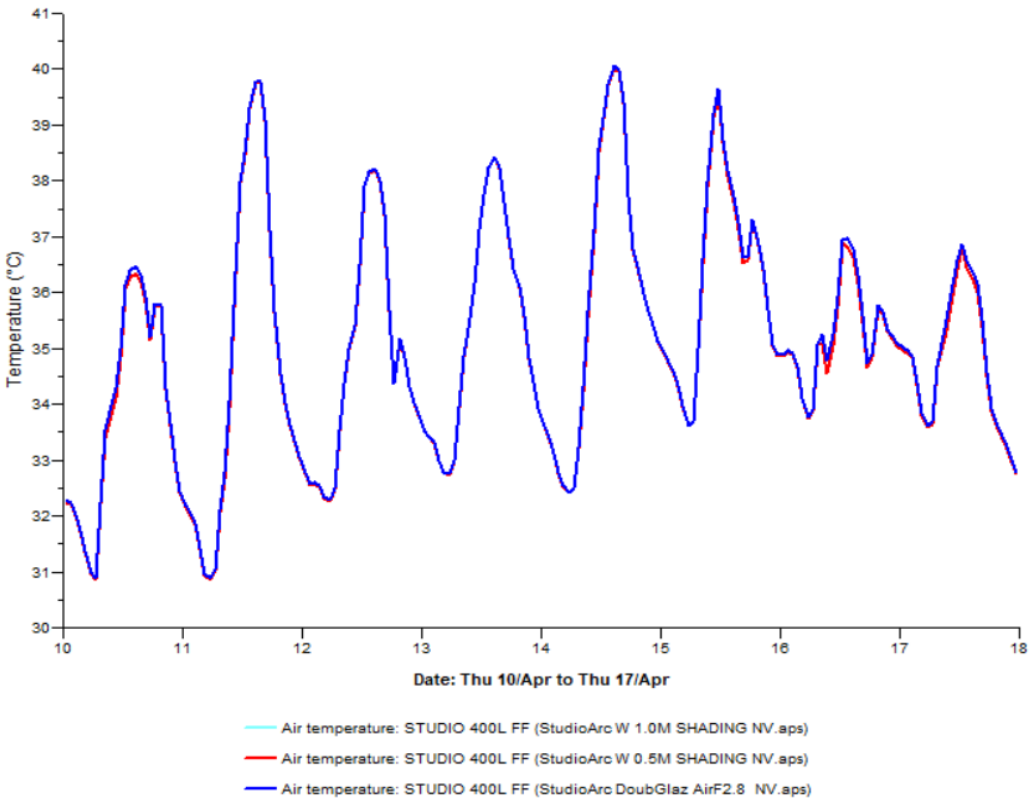

Figure 6-26 Comparison of mean annual air temperature for horizontal windows shading projections.

6.5.8 Vegetative shading

Trees were used to shade the north and south facades of the building, and the central courtyard was explored. However, the IESVE software could not accurately show the potential for evapotranspiration. Tables 6.18 and 6.19 showed that introducing these trees' vegetation led to a minimum benefit and even an increase in air temperature. This could be due to the trees blocking any breezes or winds. Even though the simulation results did not reflect the potential for evapotranspiration, they could have contributed to cooling the environment and the building. Introducing vegetation only blocks the room's access to daylight and adversely affects the occupants, so this design change was minimally implemented in the simulations.

Table 6.19 A comparison of internal conduction gains with/without vegetation in 400l Studio.

Var. Name	Location	Filename	Type	Min. Val.	Min. Time	Max. Val.	Max. Time	Mean
Internal cond	STUDIO 400	StudioArc W VEGETATI	Gain (kW)	-22.8310	09:30,10/Sep	11.0424	03:30,01/May	-0.0614
Internal cond	STUDIO 400	StudioArc DoubGlaz AirF	Gain (kW)	-22.8041	09:30,10/Sep	11.0722	03:30,01/May	-0.0588

Table 6.20 Comparison of air temperature with and without vegetation, shown in 400l Studio.

Var. Name	Location	Filename	Type	Min. Val.	Min. Time	Max. Val.	Max. Time	Mean
Air temperature	STUDIO 400	StudioArc W VEGETATIO	Temperature (°C)	22.14	06:30,27/Dec	42.43	15:30,29/Apr	31.29
Air temperature	STUDIO 400	StudioArc DoubGlaz AirF2	Temperature (°C)	22.14	06:30,27/Dec	42.49	15:30,29/Apr	31.32

6.5.9 Roof Canopy Shading

The energy efficiency of the corrugated Aluminium sheet with its high solar reflectance was used for roof shading (Figure 6-11). Introducing the shade led to a 64% increase in external conduction losses but, at the same time, a 95% rise in total internal conduction gains. This means that less outdoor heat is absorbed into the building, less heat is retained within the building, and less heat is released through the roof. Figures 6-27 and 6-28 and Table 6.20 show the effects on fabric gains through the north-facing roof slope.

Separating the sunshade material and the roof permits rapid heat disbursement. The airflow rapidly dissipates radiation which has gone through the shade, diminishing external gains. Figure 6-28 demonstrates where external conduction losses are continually higher than when there is no shade in position for each month of the year. The gap should also provide an avenue to remove heat from the cloth. However, this is not the case, as the internal gains have augmented with the sunshade. This could be because the double skin system is composed of a highly insulating lower layer. If there is no air movement between the canopy and the roof of the building, the captured heat may get absorbed and held in the building material.

Table 6.21 Comparison of heat transfer through the fabric in the Roof deck.

Simulation Test	Annual external conduction gains	Annual internal conduction gains
Double glazing (air filled) with 1m shading.	-1.1085	-0.0588
Roof Decking	-1.0741	-0.0614

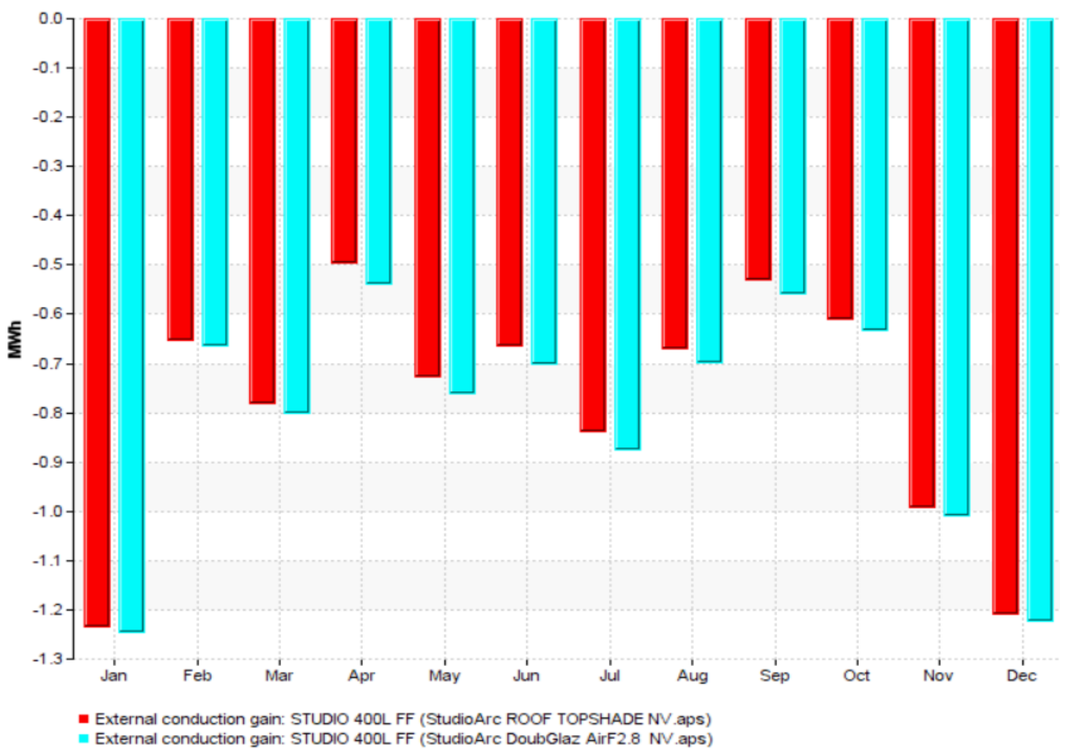

Figure 6-27 Monthly external conduction gains with and without the roof shade and Roof decking.

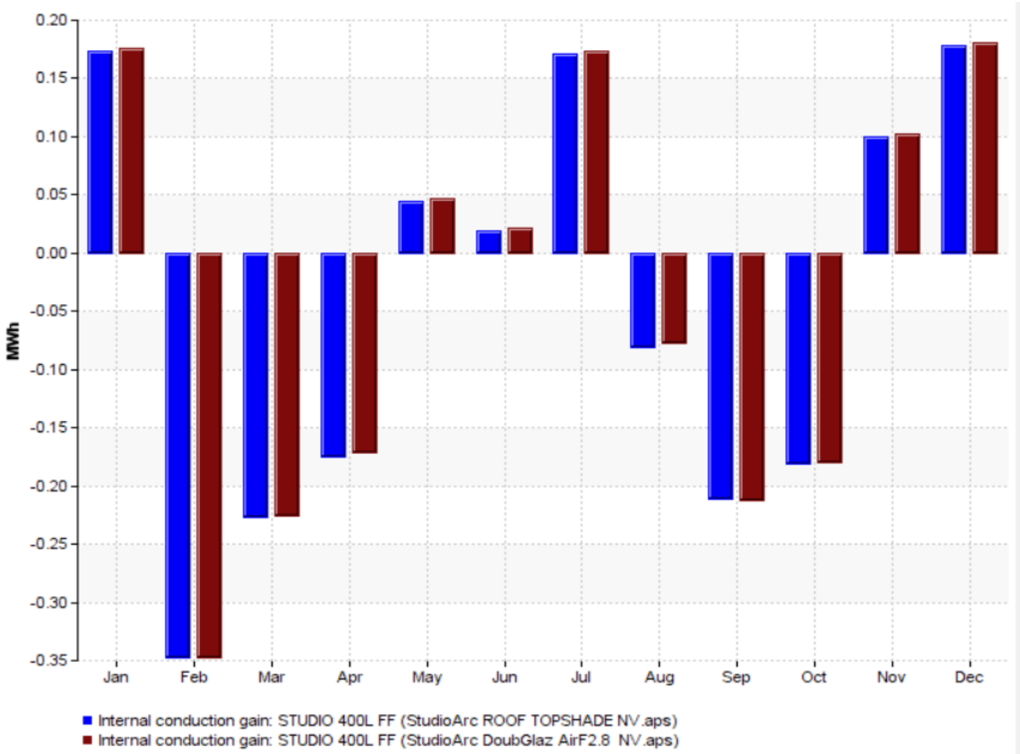

Figure 6-28 Monthly internal conduction gains with and without the roof shade and Roof deck.

Figures 6-29 and 6-30 indicate that the addition of the roof shading impacted the air temperature of the 400L studio. The Ground-floor (200L studio) room has a lower air temperature, as it is located under the 400L studio.

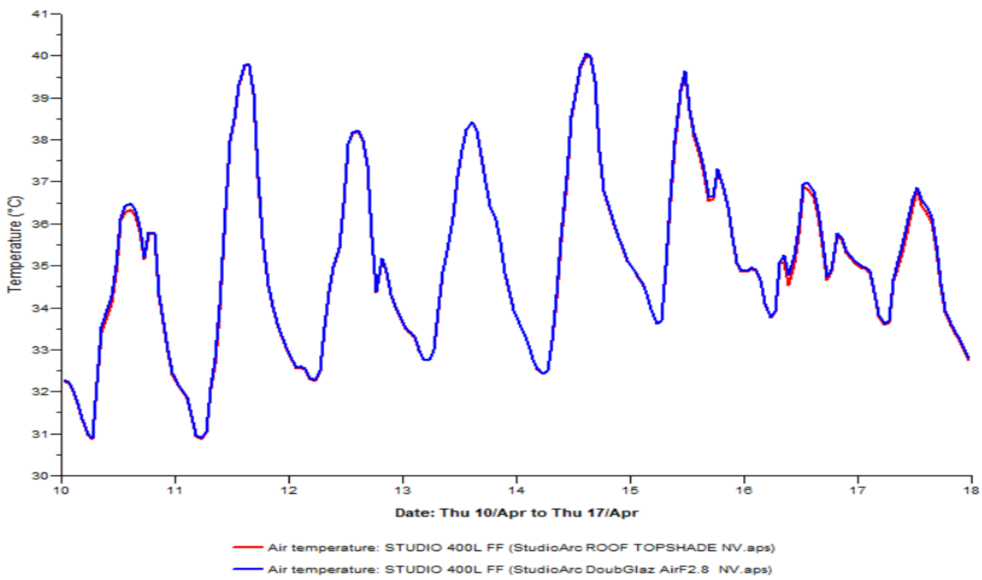

Figure 6-29 Comparison of air temperature with and without the roof shade in 400L studio at FF.

Throughout the week, the air temperature in the 200L studio room was slightly lower, with impact higher than in the 400L studio, demonstrating the impact of roof shade. Both studio rooms' minimum and maximum temperatures decreased due to the roof canopy, which altered the heat that could escape from the building, leading to a minimal decrease in internal temperatures. It could be that the outdoor airflow rate between the roof and the deck was sufficient to dissipate the heat via convection.

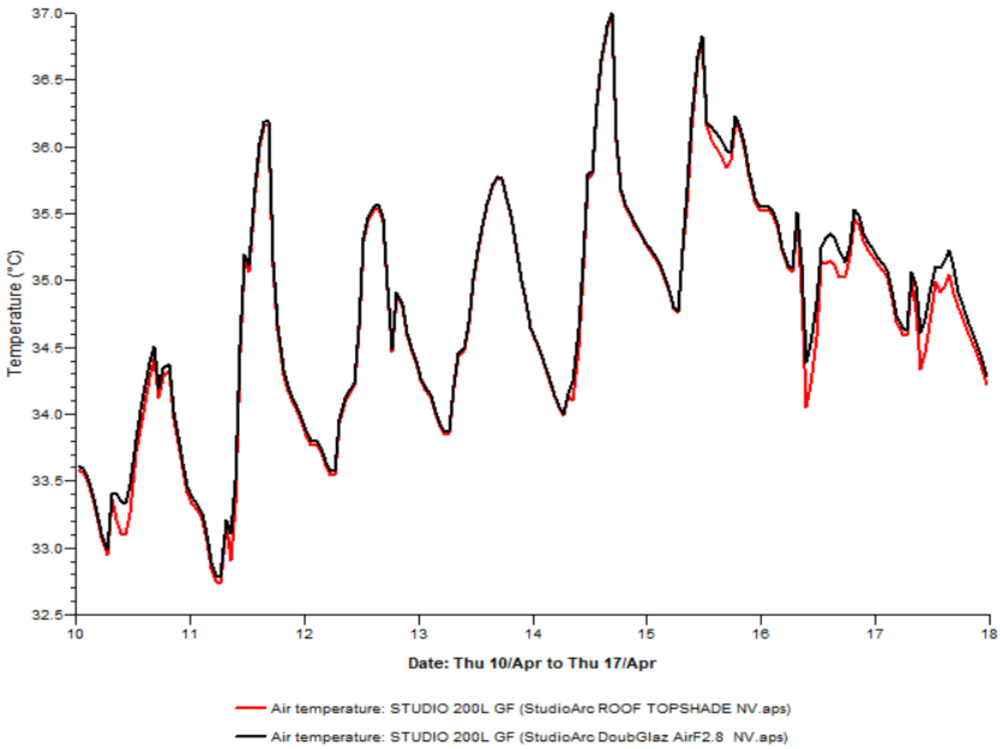

Figure 6-30 Comparison of air temperature with and without the roof shade in 200L studio GF.

6.5.10 Solar Power Potential

By mounting a monocrystalline (PV) solar panel on the roof, 1.5 meters in width by 2 meters in length, in an appropriate orientation, they can generate renewable energy while providing passive shade to help keep the building cool. An additional air gap of 0.1 meters was spaced between the panels and the roof canopy to ensure the system remains at a relatively low temperature and effectively captures energy from the sun. As illustrated in Figures 6-31 and Table

6.21, a total of 140 panels are 70 mounted on each studio roof deck. The solar panels produce a lot of roof shading. This effect is notably beneficial during the dry season (March-June), when humidity is low, temperatures are high, and solar radiation is highest. This additional shading increases the mean annual heat loss through the roof fabric by 129.31% from 0.0475 MWh to -0.0614 MWh.

Table 6.22 Comparison of internal conduction gain between the roof-top and PV installation of 400l Studio.

Var. Name	Location	Filename	Type	Min. Val.	Min. Time	Max. Val.	Max. Time	Mean
Internal conduction gair	STUDIO 400	StudioArc ROOF TOPS	Gain (kW)	-22.8310	09:30,10/Sep	11.0424	03:30,01/May	-0.0614
Internal conduction gair	STUDIO 400	PV EAST400L.aps	Gain (kW)	-22.8620	09:30,10/Sep	10.8733	03:30,01/May	0.0475

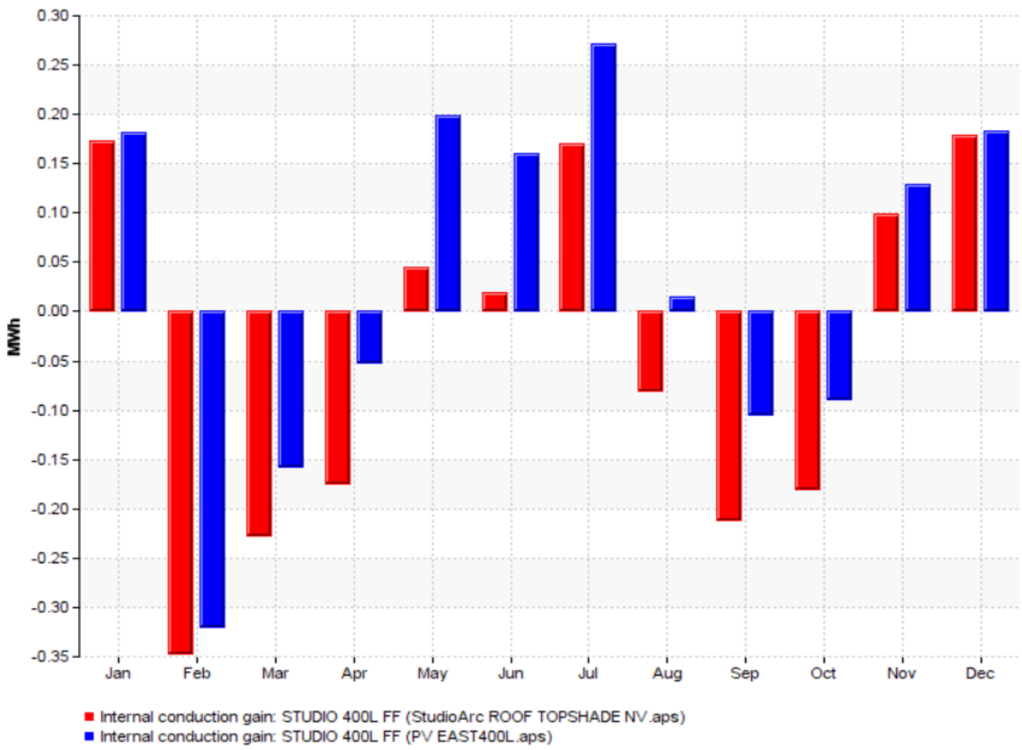

Figure 6-31 Comparison of internal conduction gains through 'Roof Slope 1' both with and without solar panel shading.

Much global research prescribed integrating solar panels as an alternative and efficient way to increase building energy and performance. Figure 6-32 displays the amount of PV electricity that could be generated with the setup of PV panels shown in Figure 6-19. The PV panels were placed horizontally at plat level to absorb the most energy year-round. Ultimately, the total PV electricity generated annually by the system is 183.37 MWh.

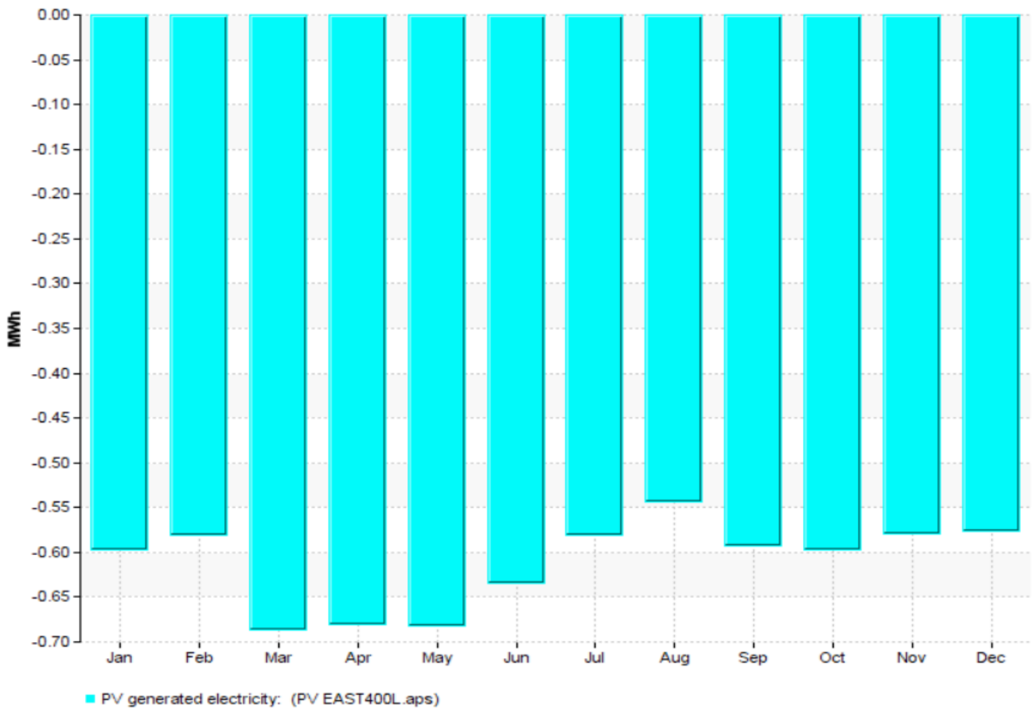

Figure 6-32 Potentials of PV-generated electricity annually using solar panels.

According to some global research, the equator is the most effective spot for solar energy since the sun's heat and light are spread evenly there. (Attah & Idowu, 2017)Korsavi et al., 2018; and Tawil et al., 2021).

6.5.11 Impact of Passive Cooling Strategies on Cooling Load

Both constructive and iterative processes observed throughout the parametric evaluation, applying passive approaches, have impacted the cooling load reductions majorly in about 7-test processes out of 8-recorded, with the original test kept as a standard for comparison. The passive cooling strategy with the highest cooling load reduction overall is the shading, regardless of the roof, canopy, or windows; this affirms the effectiveness of the climatic zone. Table 6.22 displays the results of the parametric analysis of the total room cooling plant sensible load, measured in megawatt hours (MWh). Each test was compared with the original building fabric (313.25MWh) to assess the difference. A lower value indicates a reduction in cooling load.

Table 6.23 Yearly total reduction in cooling plant sensible load after each iterative design change.

SN	**Parametric Tests**	**Total Room Cooling Plant Sensible Load (MWh)**
1	Original Building	313.25
2	Natural Ventilation	454.22
3	Fabric U-Value	304.17
4	Free Cooling	304.17
5	Infiltration & Air Tightness	303.54
6	Glazing G-Value	299.78
7	Shading Projection	296.96
8	Roof Canopy Shading	290.39
9	Solar Panel Shading	295.71

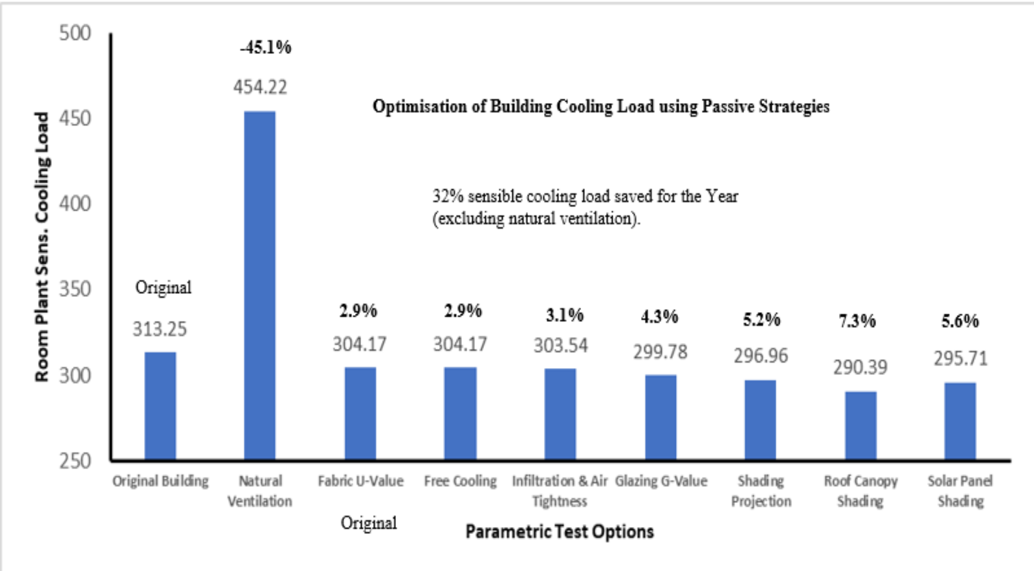

Figure 6-33 Reduction in total building cooling plant sensible load after each iterative design change.

According to Figure 6-33, introducing natural ventilation resulted in a 13.1% increase in the cooling load, while altering the roof canopy shading had the most notable effect. The smallest impact was observed in the test, which involved a

2.9% reduction in fabric u-value when the building was freely cooled. Roof canopy shading resulted in the highest reduction of 7.3%, followed by solar panel shading at 5.6% and window shading projections at 5.2%. This underscores the effectiveness of the shading strategy in each climate. Additionally, glazing at a moderate proportion reduced the cooling load by 4.3%, while cooling load reduction due to infiltration was 3.1%. The parametric results all reduce the studio's 32% cooling load.

6.5.12 Model Validation

The mean bias error (MBE) is calculated using equations 6.1 to 6.3 to validate the IES simulated model. The week-long measured indoor air temperature is compared with the simulated temperature reading, and the difference is within 1% of the model output. Thus, the model is validated and considered effective. The results in Figure 6-34 (A and B) show that the model is accurate, as the margin of error is minimal.

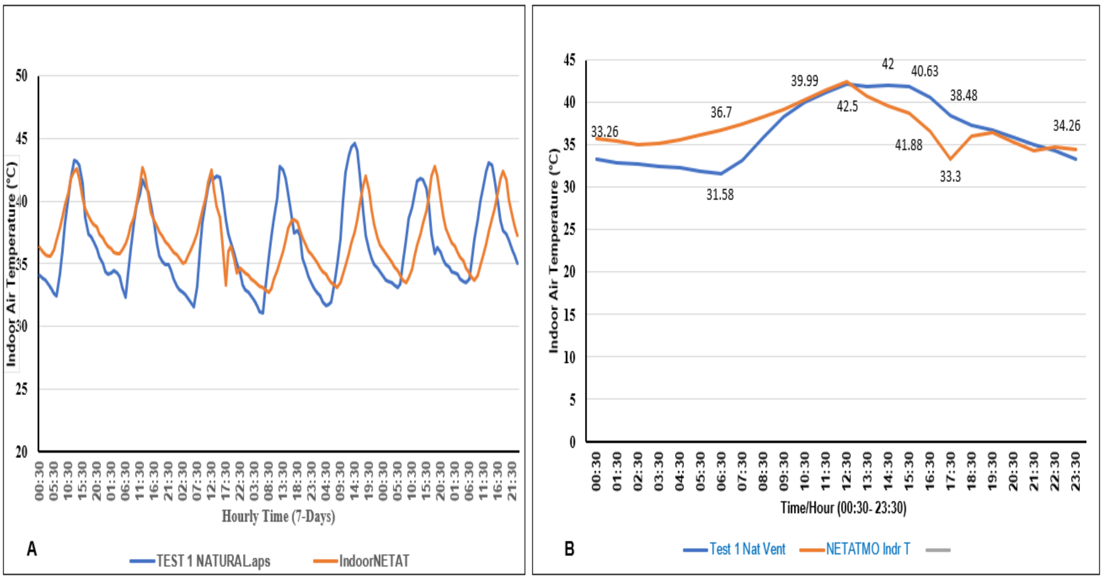

Figure 6-34 Comparison of weekly Air Temperature (A) and (B) of simulated and Measured data in April.

The calculated normalised mean bias error (NMBE)%= ±10%, and the coefficient of variation of the root mean square error should be Cv (RMSE) %= 30% for an hourly index according to ASHRAE-14, (2014) Guidelines.

According to Lin and Chen, (2018), if the recorded difference between measured and simulation readings is less than 5%, then the modelling output can be considered valid. The validation of the calibrated model indicates a reasonable modelling accuracy when using the IES software. Although it was used during the summer with a set point of 26º, the calibration considered that the classroom was air-conditioned (AC), and it was used during the summer with a set point of 26º but was switched off during the winter in November, December, and January. However, the model calibration was achieved.

6.6 Summary

The simulation results indicate that while passive cooling techniques have a limited effect on the cooling load of the building, they do decrease heat gain and exposure to direct sunlight, leading to increased occupant comfort. This research highlights the potential of passive cooling techniques in hot and dry climates. It sets a sustainable building performance improvement target of harnessing renewable energy from the photovoltaic (PV) installation that provides 184MWh of electricity generation, with potential advancement for further energy performance improvement. Despite the building's poor orientation, the cooling load reduction of 32% was recorded from the passive strategies and iterations carried out in the parametric process. However, other minimum provisions for building performance function were met, with a daylight factor (DLF) of 4.6% and illuminance levels of 563 Lux. Using IESVE software in the simulation process effectively determines the proficiency of thermal comfort, natural lighting efficiency, building performance, and passive cooling in different environments. The results of the simulation show that though passive cooling techniques have a limited effect on the cooling load of a building, they can reduce heat gain and direct sunlight exposure, which leads to increased occupant comfort. This result emphasizes the potential of passive cooling techniques in hot and dry climates. It also establishes a target for sustainable building performance improvement by utilizing renewable energy from the 184MWh photo-voltaic (PV) installation for electricity generation, which could lead to further advancements in energy performance.

CHAPTER SEVEN

7. COMPUTER MODELLING AND PARAMETRIC ANALYSIS OF THE CLASSROOM COMPLEX CASE STUDY

7.1 Introduction

This section presents the Simulation Assessment Procedure (SAP) of the case study-2 building, using the Integrated Environmental Solution tool as the subset methodology used by ASHRAE and CIBSE guidelines to assess and compare buildings' energy and environmental performance. The purpose is to complement the earlier assessment methods in the last chapters and validate and provide accurate and reliable assessments. tests to be conducted include Building Modelling Calibration, Fabric Gains Test, Natural Ventilation and Infiltration Test, Glazing Test, Shading Test, Optimization of Building Cooling Load, and Building Upgrade and Maintenance.

Table 7.1 The Parametric Test and Process

S/no	Parametric Test	Process and Analysis
1.	Building Modelling Calibration	Design of simple model, energy model, input building specs., fabric construction, and materials template
2.	Fabric Gains Test	Testing internal and external gains
3.	Natural Ventilation and Infiltration Test	Natural, auxiliary, and infiltration rates.
4.	Glazing Test	Testing glazing types in varying specifications.
5.	Shading Test	Windows, roof, canopy, and vegetative.
6.	Optimization of Building Cooling Load	total building cooling plant sensible load after each iterative design change
7.	Building Upgrade and Maintenance	Applying optimal results to develop maintenance and retrofit framework
8.	Renewable Energy	Solar PV panel integration will improve energy supply.

The simulation process in Table 7.1 involved iterative design changes to assess their impact on the cooling load, occupants' comfort, and fabric gains. Changes were made in a specific order to maximize their potential. For example, after increasing thermal mass, natural ventilation was introduced, and night cooling was implemented after adjusting u-values. Infiltration was then adjusted to reflect improved insulation. Window efficiency was improved, and shading was added to reduce incident radiation and solar gains.

7.2 Parametric Analysis of Classroom Complex in IES-VE

Using IESVE simulation software for thermal comfort assessment and energy efficiency analysis, dynamic simulation techniques were employed in this parametric study to understand the key factors. Adopting this modelling tool made it easier to understand the impact of various thermal indices, natural ventilation techniques, and exterior shading on the thermal performance of higher education facilities by employing simplified architectural models. Additionally, adopting simplified building models was useful since it required fewer inputs and provided a better connection between the direct inputs and the outcomes.

The main objective of this parametric study was to quantify the effects of implementing the chosen passive design strategies in typical contemporary university buildings in the hot-dry climate zone of Nigeria, demonstrating their potential to reduce instances of overheating that result in the use of active cooling outside of extreme (hottest) times of the year. Based on the results presented in Chapter 3, which were also discussed in a paper developed as part of this study entitled “Review of Strategy for Assessing the Thermal Performance of Institutional Building Form in Hot-Dry Climate of Nigeria,” Bena et al. (2019) it was proposed that the use of multiple strategies, in the passive assessment of higher education building could significantly contribute to improved indoor thermal conditions in facilities in hot-dry climate of Nigeria. The parametric study in Chapter 5's simulations lays the groundwork for the structure's maintenance and retrofitting.

7.2.1 Simulation Basis

Categorisation of the performance of external shading elements for solar heat gain control and thermal comfort optimisation of Educational buildings in the hot/dry climate of Nigeria applicable to the local latitude of 12.3°N and longitude of 4.2°E has not been widely investigated, (Arup, 2016). Originally, ASHRAE and CIBSE guidelines were used because the NESP and BEE documents are still being developed. Currently, the Nigerian Energy Support Program and the National Building Code are the two regulatory documents that recommend using passive strategies and techniques to improve building performance and efficiency. However, this will help bridge this gap in the existing literature; simple maintenance frameworks were developed to help built professionals ability to provide the minimum thermal comfort by altering the building fabric elements, different types such as the provision of external shading devices, glazing types, shading the roof by laying photovoltaic (PV) panels at the rooftop while servicing as a renewable source of energy, the same process was followed in (Chapter 5). The Climate Consultant software prescribes horizontal shading elements as the most effective in the climatic zone.

A series of dynamic simulations were run on the building to derive the fabric elements' average monthly solar heat gain values from ascertaining how solar insolation affects different sides of the building, specifically where openings are against the orientation and the indoors of buildings and how overheating affects the occupants (staff and students) for a typical year. Other fabric elements such as roof, window, and glazing were assessed and improved, and structural shading devices were developed in the positions of walls/windows, which were simulated for retrofitting and maintenance. Shading against solar radiation is a viable passive building retrofit and maintenance strategy in hot/dry climates.

7.2.2 Simulation using IESVE Software

IESVE Integrated Environmental Solutions Simulation Software is a simulation and analysis tool utilized for the parametric process. The tool is also known as virtual environment software (IESVE), gives the information needed to make more responsible judgments in modelling and assessment of buildings (Mihara et al., 2019). The software often creates a comprehensive approach to the performance of the building by combining data from the HVAC and ventilation, daylight, artificial lighting, and CFD sectors. The optimal requirements and solutions can be specified by knowing what works best for occupant happiness and significantly greater energy efficiency (Vethanayagam and Abu-Hijleh, 2019; Lau et al., 2016). The important functions of IESVE software that led to its selection and utilization have been discussed in the previous Chapter.

7.2.3 Method, Process, and Assumptions

The parametric process began with designing and developing the building model in IES VE. Many assumptions were made based on the weather file of Birnin Kebbi, which was integrated into the VE, the original fabric specifications, adopted together with their corresponding u-values. In the model design, each floor is independent of the others; consideration for access between them has not been given. However, the templates selected ventilation and infiltration as standard provisional values. Composite elements u-values and g-values were assigned in the software construction template, and the model design was simplified and short of details. The initial processes and methods followed were modeling, simulation with modified variables, and achieving an optimal model.

7.2.4 Simulation Methodology

Following are some steps in using the simulation program IESVE for the building assessment: The first step was using the "Model IT" and "Building Template Manager" features to model the geometry and original case study building envelope specifications. To evaluate energy use and occupants' thermal comfort, a thermal template was assigned to the model in which ventilation and infiltration airflow rates, number of occupants, and solar indoor heat gains were specified. Each choice was investigated for its incremental benefits on thermal performance and energy levels. To reduce heat transfer into the building by conduction, convection, and radiation, a mix of heat removal and heat gain prevention strategies was investigated. Natural ventilation, envelope fabric u-values, free cooling, roof and window shading, and higher air tightness were some of these measures. The same simplified parametric workflow process and diagram in Chapter 6 demonstrate the methodology adopted.

7.3 Building Geometry and Modelling

Figure 7-1 (a), (b), (c), and (d) show the reference building model and the elevations and plan views created using ModelIT. The fabric specifications in Table 7.1 of the building were set based on the u-values of construction elements provided in the case study information, and the associated compositions of construction materials were assigned to the *ApachePro* template.

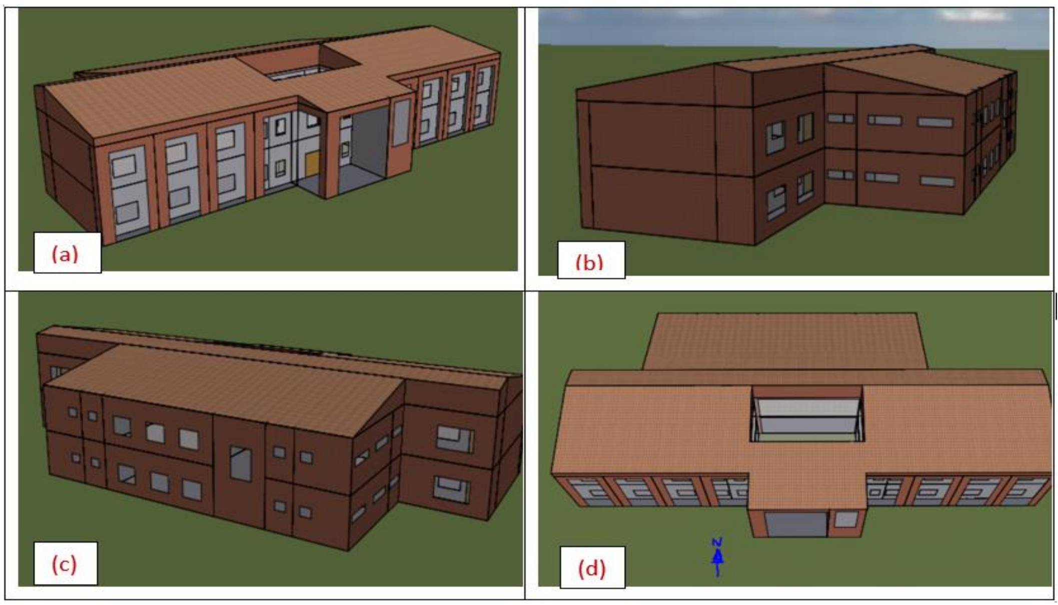

Figure 7-1 Existing Classroom building isometric views (a) South elevation, (b) West elevation, (c) North elevation, (d) Roof top view.

Table 7.2 Building fabric and Construction materials specification.

Fabric Element	**Composition**	**U-value (W/m^2K)**
External Walls	18mm external wall plaster; 230mm hollow Sandcrete Conc. Blocks: 12mm internal wall plaster	1.36
Doors	37mm hollow in steel framed	2.1
Roof	0.045mm Aluminum roofing sheet on steel hollow pipe steel-struts roof members	7.28
Internal walls (Partition)	18mm external wall plaster; 230mm hollow Sandcrete Conc. Blocks: 12mm internal wall plaster	1.36
Windows	Single glazed pane (6mm)	6.9
Ground Floor	10mm tiles finish, 20mm cement screed, 150mm dense concrete 300mm hardcore fill.	3.72
Upper Floor/ Ceiling	190mm Cast in-situ concrete	1.8

i. Assigning Thermal Template

The building's operating parameters were set using ‘Building Template Manager’. The template's input includes the occupancy profiles, lighting profiles, air exchanges, building activity, and internal gains. Throughout the building's optimization, these design conditions were kept constant. Any changes to the loads or gains only reflect the physical amendments made.

Figure 7-2 shows the occupancy profile set for the building during weekdays. The occupancy is set as ‘strictly off’ during weekends. Considering the building function for teaching and learning, it is most likely that the operating hours stay this way for most weeks of the year unless for an additional function unique to the design courses offered by the faculty of Environmental Sciences of the University, for example, design/construction presentation that lasts longer in time allocation. However, the building is at full occupancy between 9 am and 3 pm and half occupancy to account for people's gradual arrival and stay before and after assigned lecture periods, respectively.

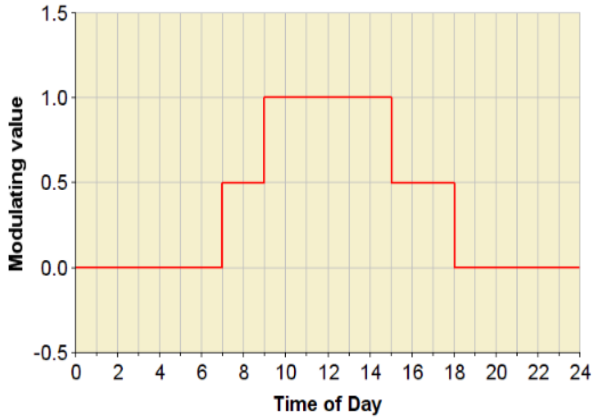

Figure 7-2 Daily weekday occupancy profile

For all simulations, the cooling set point was turned off as the purpose of this study is to investigate passive cooling strategies. Where the reduction in cooling load has been used to demonstrate these effects, the cooling set point has been set in association with the occupancy profile. In line with the 'Effective Temperature index for thermal comfort range in summer for educational building in climates', by ASHRAE handbook (2021) and Olesen, (2012), the set point was set at 26°C. The building's internal gains and air exchanges were set as follows (in association with the occupancy profile) based on CIBSE Guide A (Fergus & Marialena, 2021). See Table 7.2, 7.3.

Table 7.3 IESVE Thermal template internal gains and power consumption.

Type	Maximum Sensible Gain	Maximum Latent Gain	Occupancy	Max Power Consumption	Meter	Variation Profile	Dimming Profile
Fluorescent Lighting	12.000 W/m²	-	-	12.000 W/m²	Electricity: Meter	New Annual Occupancy	on continuously
People	53.000 W/person	40.000 W/person	10.000 m²/per	-	-	New Annual Occupancy	-

Table 7.4 Input profile for infiltrations and air exchanges in the building.

Type	Exchange Reference	Max Flow	Unit	Variation Profile	Adjacent Condition
Auxiliary Ventilation	Auxiliary ventilation	10.0000	l/s/person	New Annual Occupancy	External Air
Infiltration	Infiltration	0.500	ach	on continuously	External Air

The simulation was conducted by gradually adding each design change to the existing case. The changes were made in the order shown in the figures and charts to ensure that each was fully exploited, which allowed the effects of the changes on cooling load, occupant comfort and fabric gains to be determined. For instance, natural ventilation enabled heat to escape from the building once the thermal mass had increased. This instance was demonstrated in Shanmugga & Kannamma, (2022), who argued that thermal comfort inside classrooms of institutional buildings depended on the effects of air temperature, relative humidity and wind velocity, and the building's position and orientation.

Night cooling was more effective when coupled with thermal mass because of the heat storage possibilities and was applied after changing the materials' u-values. In addition, infiltration was adjusted from the actual and natural states as the insulation of the building was improved. As the building became more airtight, the air rate changes per hour decreased. Finally, the windows were replaced with more energy-efficient ones, thus boosting the envelope performance. The last four optimizations made to the building model were all focused on shading, that is reducing the amount of incident radiation on the building and the solar gains.

7.3.1 Simulation of Building Fabric External and Internal Heat Gains

The amount of solar radiation that strikes a building can greatly impact its structure. Increasing fabric insulation on roofs, windows, and openings is done thoughtfully in hot/dry climates, as high thermal mass structures control the release of heat efficiently. The shade of these building elements is the most important strategy for reducing indoor heat. To take advantage of a thermal lag effect, in which day-to-night temperature variations are greater than 10°C, the building should be well-shaded and facing the right direction.

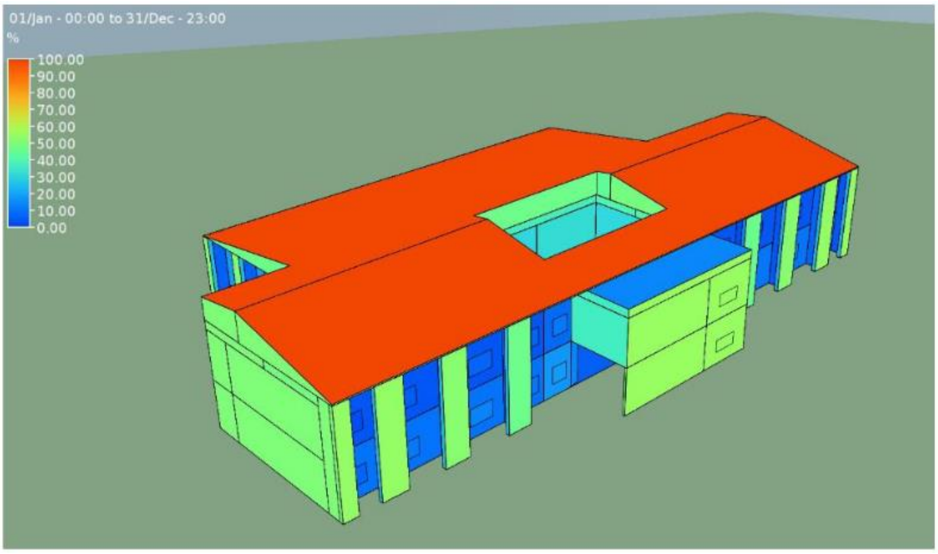

Figure 7-3 Percentage of solar irradiation incidents on the building envelope

Figure 7-3 illustrates the amount of solar irradiation that hits each side of the simulated building with IES software. The roof receives the most sunlight and heat of any part of the building, as it remains exposed to the sun's rays even when it passes directly overhead. Viewing from Figure 7-3, the roof receives over 90% more irradiation than any other façade.

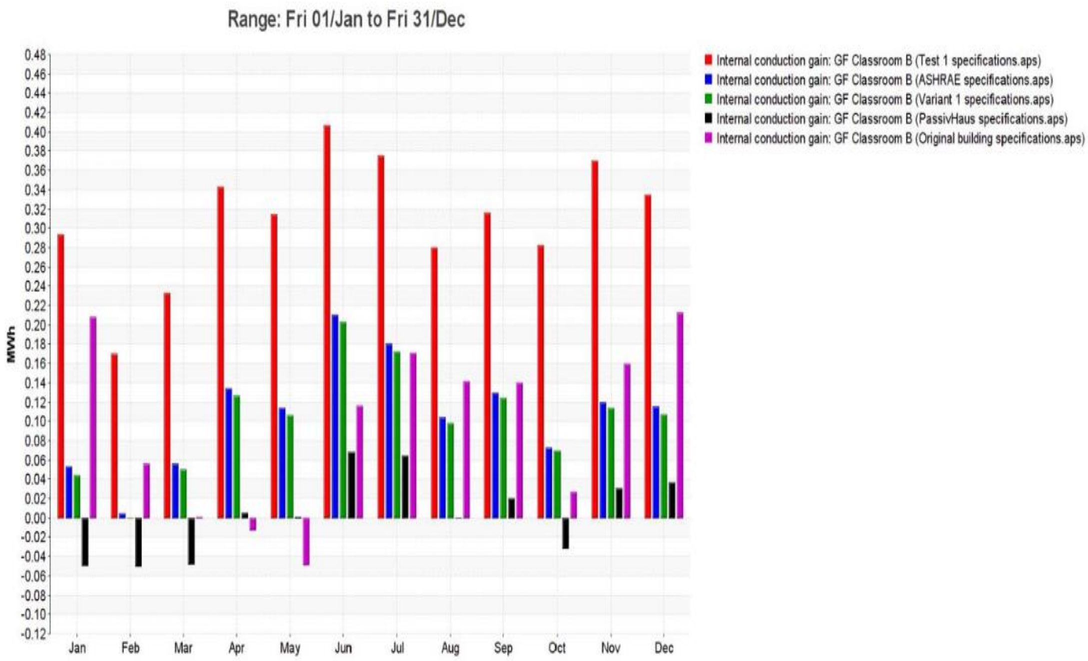

Figure 7-4 Comparison of internal conduction gains for fabric test, in 'GF Classroom B'.

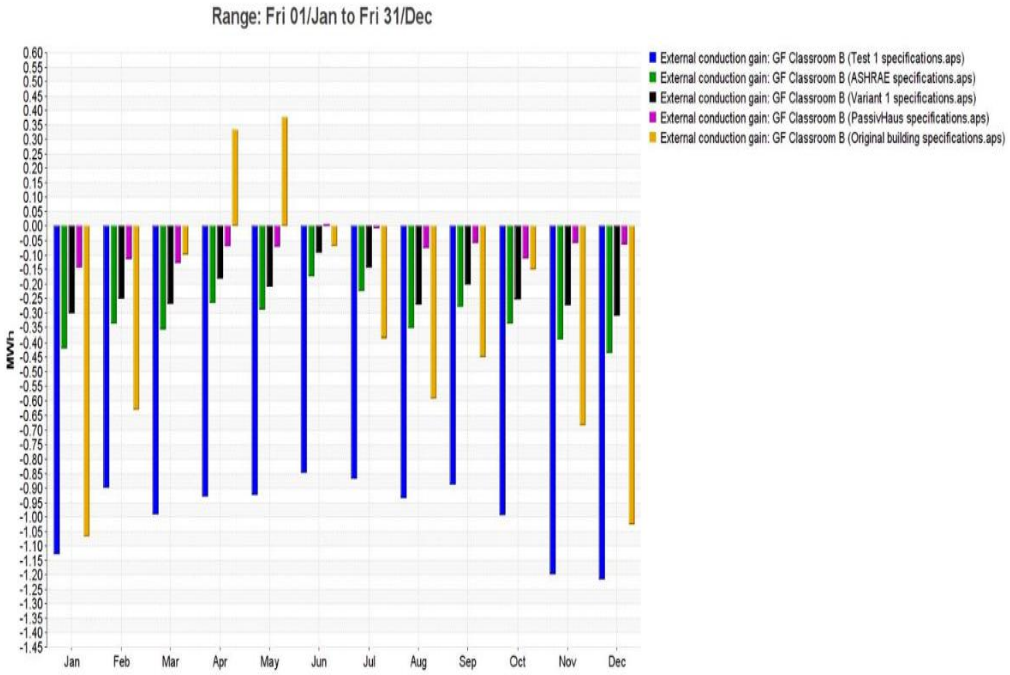

Figure 7-5 Comparison of external conduction gains for all fabric test, Classroom B'.

The results of the simulation in Figures 7-4 and 7-5 illustrate the effect of different u-values on the internal and external conduction gains of a building. Internal conduction gains are comprised of any sources of heat emanating from within the structure, while external gains refer to the heat coming from outside sources, generally taken in by the building itself. The data indicate that when the u-value is reduced, there is increased heat retention which may not be beneficial. Negative external conduction gains represent a heat loss to the environment, while positive internal conduction gains point to the building taking in more heat through its internal surfaces. Heat loss and gain by building fabric affects the increase/decrease in indoor temperature and alter it, the difference between outside/inside temperature can provide good values of the actual indoor air temperature.

7.3.2. Solar Radiation and Building Form.

The fabric construction test has the highest u-value and, thus, the greatest heat transmission coefficient. This explains why its outside conduction gains (Figure 7-5) change from positive to negative over the course of the year. Though the fabric can lose heat, the rate of heat absorption is greater than the rate of heat loss. The "PassivHaus" design guide is a sustainability certification rating tool, a recognized system in Europe and mainly used in cold climates regions but does not provide much passive cooling for the building (NNBC, 2016). Although it is the only test that produced negative indices of internal conduction gains other than the first construction, the building can't lose as much heat as indicated in tests (as is shown in Figure 7-4). The ASHRAE and Variant 1 tests have comparable outcomes regarding their gains. The building elements heat gains from the inside are always positive, and the heat lost outside is usually equivalent. This can mean that these two tests are not very helpful in providing passive cooling to improve thermal comfort, as the heat gains and losses are equalized over the year.

7.3.3 Sun-Cast Simulation on Building Fabric

Test 1, which involves only a heavy construction roof and all other constructions being light, has the greatest heat gain through the fabric by a large margin (Figure 7-3). This is attributable to the roof being exposed to the most solar radiation and storing thermal energy due to its high thermal inertia against temperature changes. Since the dry bulb temperature remains constant throughout the day, the heat cannot be released, thus causing excessive gains. The external conduction gains in Figure 7-5 demonstrate that this test can release heat back into the environment. The thermal lag created by the roof retains the heat for a long period during the peak daytime temperature. However, convection air movement can draw the heat out of the high-mass fabric and transfer it back into the surrounding environment, even when the diurnal temperature is low.

Table 7.4 displays the contrast between the internal and external conduction gains for each experiment presented in Figures 7-4 and 7-5. Each comparison is negative, implying more warmth is lost than obtained. Consequently, all the u-values tested are losing heat to the environment. Surprisingly, the only one that demonstrates an improvement from the original conditions is ‘Test 1’. This can be partly attributed to the roof receiving more solar radiation, necessitating a higher thermal transfer coefficient to counter it.

Table 7.5 Summary of fabric gains for each of the fabric tests in 'GF Classroom B'

S/No	Test options	Annual mean internal conduction gain (MWh)	Annual mean external conduction gain (MWh)	Difference (MWh)
1	Original	0.4721	-1.0679	-1.54
2	PassivHaus	0.0053	-0.1020	-0.1073
3	ASHRAE 90.1	0.1476	-0.4396	-0.5872
4	Variant 1	0.1386	-0.3134	-0.452
5	'Test 1'	0.6504	-1.4891	-2.1395

Despite the high air temperatures and humidity levels throughout the day and night, lightweight and heavyweight construction combined with heat storage capabilities can reduce the cooling load during peak times, and the low thermal mass enables the heat to be expelled quickly.

To ensure the comfort of those in the building, the chart below (Figure 7-6 Test 1) shows the number of comfortable occupants over the course of the year. This optimization method met the PassivHaus specifications and had the most positive effect. When the outdoor air is at its hottest, the roof fabric's increased heat storage capacity helps keep the indoor air temperature from getting too high, keeping occupants' content. The percentage of individuals who are not content remains high from March to October, with an average of 87.42%. However, during the winter, there is a decrease, and the yearly average of unsatisfied individuals drops to 80.32%, a decline of 8.13%.

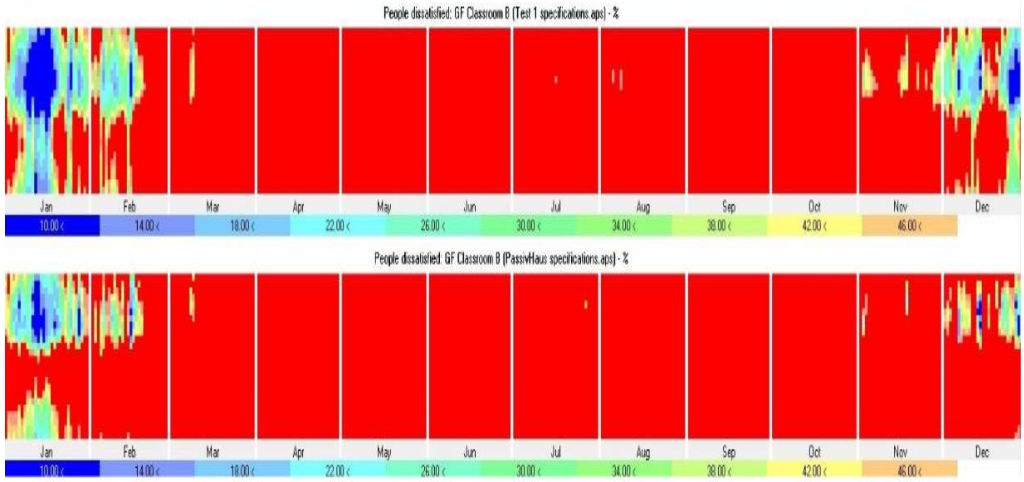

Figure 7-6 Comparison of people dissatisfied between the most and least effective fabric test, in 'GF Classroom B'.

i. Fabrick U-Value

Table 6.5 below displays the different U-value specifications chosen for examination in this construction. This selection incorporates completely decreased values and individual components to assess how the building reacts to thermal capacity and heat within the envelope. These values were adjusted using the Building Template Manager. The values also include the actual values and the regulations they are based on, when applicable.

Table 7.6 Fabric optimization of building u-values

Building Elements	**Original**	**U-Value (W/m²K)** **PassivHaus**		**ASHRAE 90.1**		**Variant 1**		**Test 1**
		Regulated	Actual	Regulated	Actual	Regulated	Actual	
External Walls	1.36	≤0.15	0.136	0.857	0.857	0.8	0.801	1.361
Roof	7.28	≤0.15	0.142	0.153	0.153	0.37	0.372	0.104
Floor	1.8	≤0.15	0.150	0.857	0.857	-	0.785	1.803
Ground	3.72	-	0.150	0.857	0.857	-	0.786	3.719
Door	2.1	≤0.80	0.795	0.857	0.857	-	0.794	2.197
Internal Partition	1.36	≤0.1-0.15	0.151	0.857	0.857	-	0.800	1.361

ii. Simulation of building free cooling and nighttime purging

At night, the heat gained throughout the day is released using the Apache system's "changeover mixed mode free cooling-natural ventilation" system. This system involves utilising natural ventilation to cool the interior during occupancy hours. When the outside temperature is lower than the interior and can provide cooling benefits (generally in the evening), windows are opened to take advantage.

7.3.4 Simulating Natural Ventilation

To illustrate the consequences of whole-building natural ventilation, the building's entries (including both windows and doors) were set to be able to be opened in MacroFlo. The doors and top-hung windows were given an openable proportion of 100% and a maximum opening angle of 30° throughout the building's operating hours.

i. Infiltration and Air Tightness

The air tightness of a building directly impacts its rate of infiltration, and it is the only factor that can be optimised. Other factors that contribute to the infiltration rate, such as wind speed and direction, orientation, and the temperature difference between the interior and exterior, remain constant. If the thermal envelope is sealed tightly, the air is less likely to enter and exit the building.

The iteration process explained in the previous chapter was followed by changing and testing Air exchange values while running the simulation. To check this, the Building Template Manager was used to simulate in Apache with initial infiltration rates of 0.5 ACH, 0.35 ACH, 0.3 ACH, 0.25 ACH, and 0.2 ACH. Tight and sealed buildings retain air inside spaces or zones. This often becomes a disadvantage when hot air is trapped inside the room space in the building, when cooling is required, causing discomfort.

ii. Glazing Values Adjustment

G-values are used as a measure of the proportion of the sun's radiation that can go through a window. In places with hotter climates, a lower g-value is more desirable as less of the sun's radiation can enter the building. The classroom complex has the same characteristics of glazing type, sizes, and value as case study A. To make these adjustments, the Building Template Manager was used to alter the glazing g-values and fabric u-values. Table 4 displays the various glazing choices that were tested. Window glazing adjustment is effective in indoor lighting provision and regulations.

Table 7.7 Window specifications

Glazing type	**U-Value (W/m^2K)**		**G-Value**	**Cavity size (mm)**
	Suggested	**Actual**		
Original Single Glazed	-	6.855	0.8205	-
Double glass (Air-filled)	2.8	2.8077	0.7082	12
Tripple glass (Air-filled)	2.1	2.0970	0.6192	12
Tripple Glazing (Low E, εn=0.05 Argon filled)	1.3	1.2983	0.6207	16

7.3.5 Simulating of Building for Shading

To demonstrate the impact of shading on reducing solar gains, simulations were conducted with lightweight material to create structures such as hoods, awnings, horizontal louvres, and recesses erected over the windows. Vegetative shading was also simulated. Next are explanations of applications carried out for passive shading simulation.

i. Shading device

These provide a protective structure over the windows to protect against direct solar radiation. Multiple simulations were conducted to assess the advantages of the shading projections on classroom B. The canopies were projected away from the edge of the building between 0m and 1m in 0.5m intervals, as shown in Figure 7-7. The IESVE software was then used with the FlucsDL feature to analyze the daylight entering the spaces and the VistaPro feature to compare it to the solar gains. The most appropriate shading type and size were identified as they both minimized solar gains and allowed for adequate natural light.

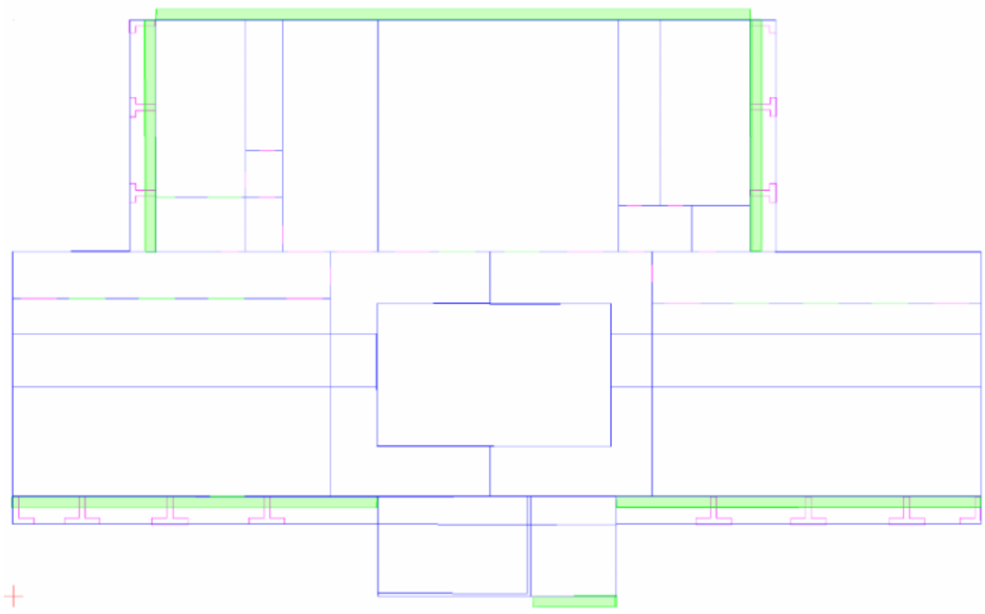

Figure 7-7 Shading projections in (green colour) shown in plan.

ii. *Vegetation Shading*

The IESVE software's component modeller was used to download several trees from an online library and add them to the model with ModelIT. Figure 7-8 displays the chosen vegetation type, which is 10 meters tall and 7.7 meters wide. Three trees are on the south and north facades of the building, with one placed in the central courtyard. SunCast and Apache were used to model the trees' shading effect but not their evapotranspiration properties. Much research has recommended the efficiency of using natural vegetation, such as large trees, to provide shade in building envelope; trees with good foliage significantly contribute to air filtration.(Trepci et al., 2021; Mahmoud & Abdallah, 2022; and Abdallah, 2022).

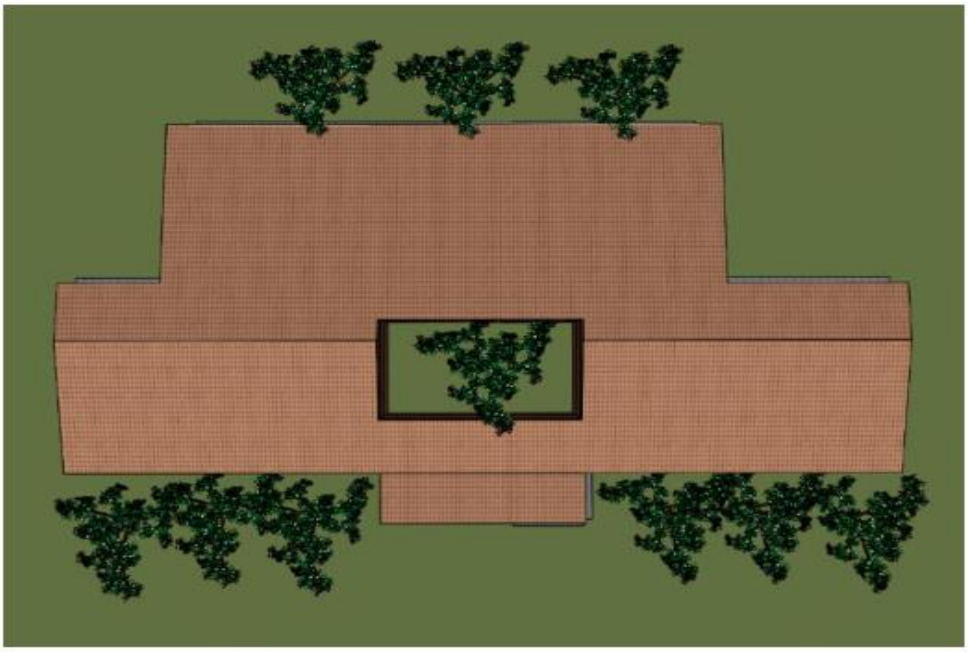

Figure 7-8 Vegetation placement around the building.

iii. *Roof Shading Canopy*

The canopy, which provides roof shading, is system designed and crafted from solid aluminium panels (as seen in Figures 7-9) and is projected 2 meters above the roof at its lowest point.

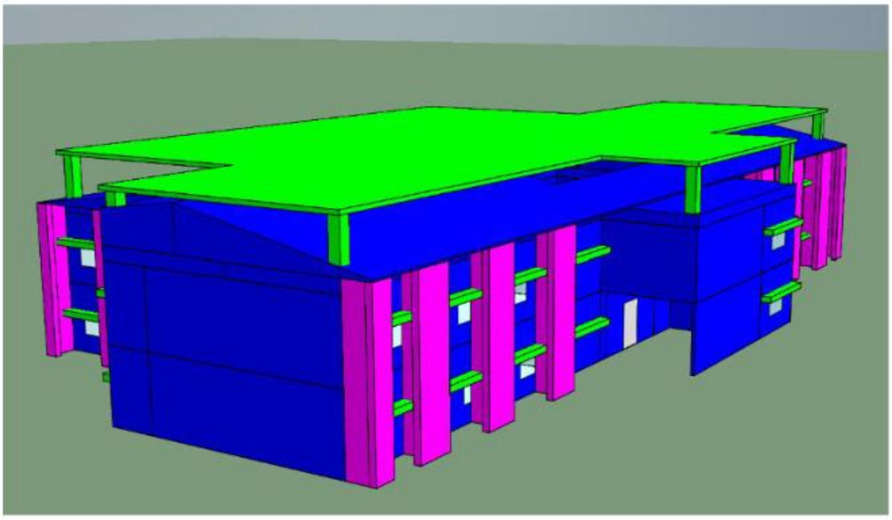

Figure 7-9 Projected roof canopy shade (green); system design using IESVE ModelIT.

Utilizing ModelIT, the design alteration was defined as a 'local shade'; later, it was further excluded from calculations concerning heat gain/load. Furthermore, the canopy will serve as a foundation on which photovoltaic panels can be mounted for renewable energy resources. Aluminum is used for the canopy because its lighter in weight, see Table 7.7.

Table 7.8 Roof shade construction template input

Material	Thickness mm	Conductivity W/(m·K)	Density kg/m³	Specific Heat Capacity J/(kg·K)	Resistance m²K/W	Vapour Resistivity GN·s/(kg·m)	Category
[ALM1] ALUMINIUM	12.0	0.0500	2800.0	896.0	0.2400	3000000.000	Metals

iv. Solar Panel Shading

ModelIT was used to fit photovoltaic panels to the roof canopy, covering the entire 906.6m2 surface with 72 Monocrystalline Silicon cells. As illustrated in Figure 7-10, this results in a view of the solar PV panel setup on the top-level shade, each panel measuring 2 x 1 metres.

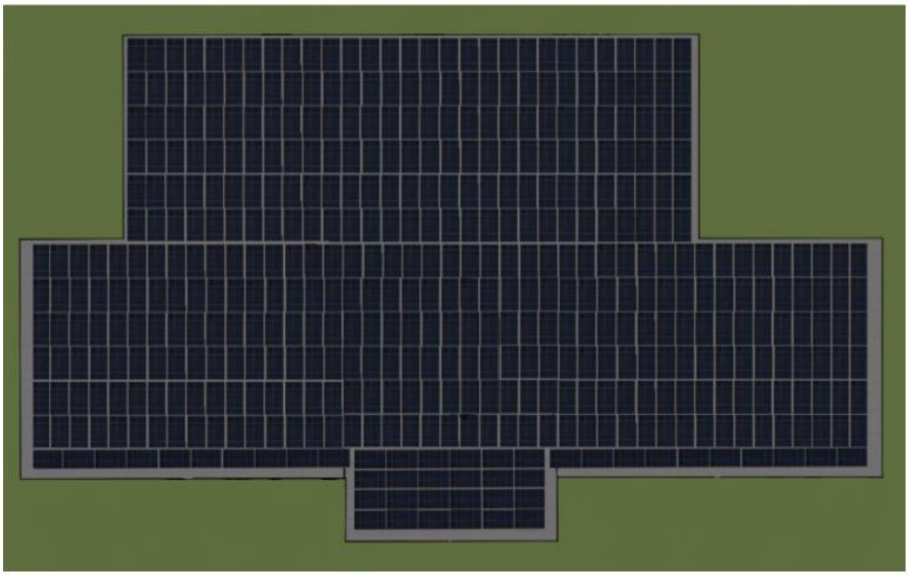

Figure 7-10 Solar panel layout and arrangement on the roof canopy.

7.4. Building Simulation Results and Analysis

The energy simulation software was applied to the case study building to evaluate the thermal performance and solar analysis when applying various passive cooling strategies discussed in the second chapter. Each simulation was performed over one year, and the results were presented for the most sweltering week of the year (from the 11th to the 17th of April 2021 in the wet season) and the hottest day (Tuesday 13th of April 2021). For comparison, the temperatures and humidity of the week of the 10th to the 16th of January 2021 (in the dry season) were also considered. For thermal analysis, Ground Floor Classroom B' was chosen as it is the most frequently occupied throughout the building and has enough glazing to illustrate the gains accurately. Figures 7-11 and 7-12 compare the internal and external temperatures of the classroom in B at ground floor (GF) chosen area over the entire year and for the week. (See Appendix VII -Classroom IES-VE Model Report)

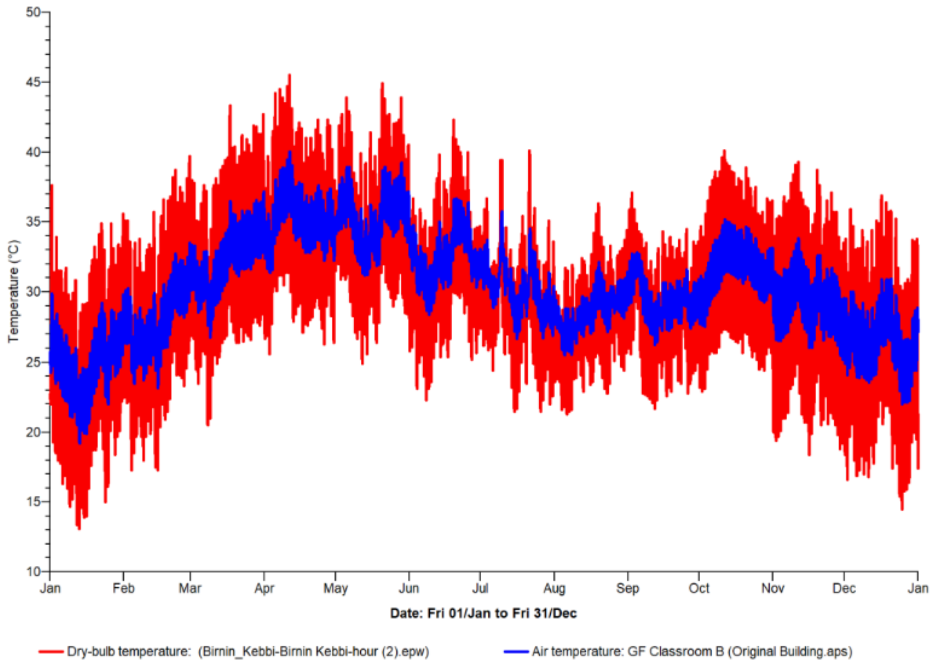

Figure 7-11 Comparison of annual external and internal temperature, shown in 'GF Classroom B'.

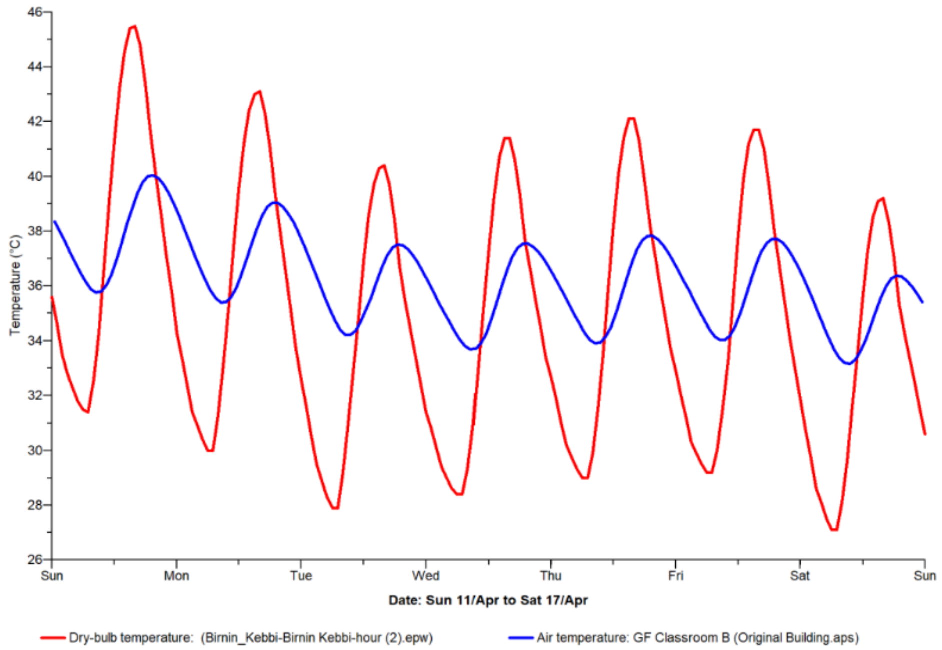

Figure 7-12 Comparison of weekly external and internal temperature, shown in 'GF Classroom B'.

7.4.1 Simulation of Classroom Complex for Passive Cooling

The parametric test results of passive cooling process of the classroom complex was presented under; natural ventilation, building gains, night cooling (free), infiltration and air tightness, glazing adjustments, and shading (projected, canopy, roof and PV).

7.4.2 Natural ventilation

The impact of natural ventilation on the air temperature in 'GF Classroom B' is demonstrated in Figure 7-13. The results show a temperature increase of 4.81°C between the minimum room temperatures, with a difference in average temperature of 1.19°C. Similar studies indicate that achieving the optimum temperature in buildings through natural ventilation alone is difficult. In hot climates, ventilation still contributes to the rise in interior temperatures (Olatunji Jimoh & Umar, 2021).

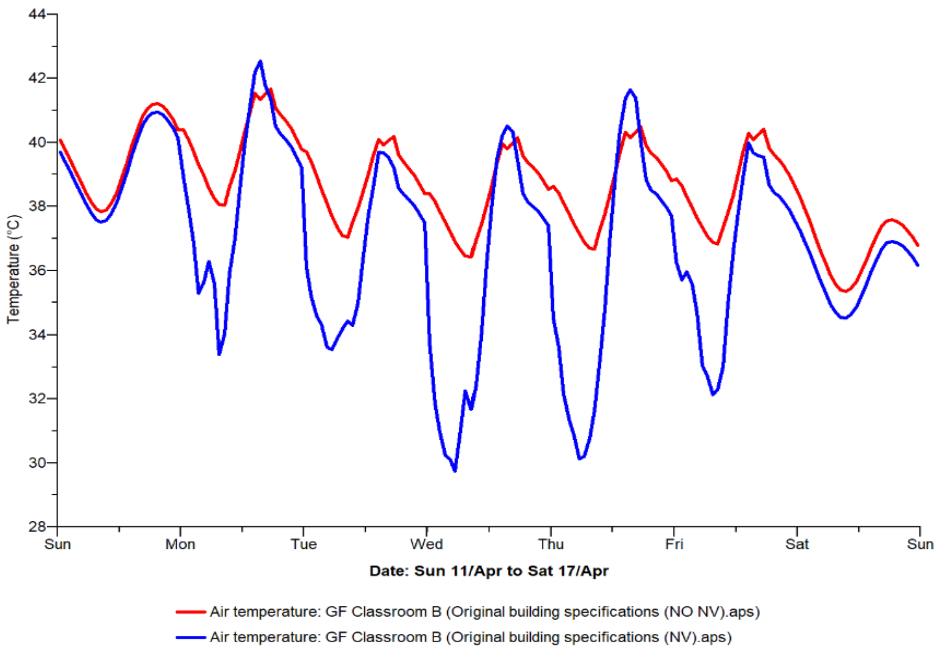

Figure 7-13 Comparison of indoor air temperature with and without natural ventilation, shown in 'GF Classroom B'.

When comparing Figure 7-14, which displays the number of unsatisfied indices of occupants when natural ventilation is not sufficient, the biggest change is seen between 1 a.m. and 2 p.m. This could be because of decreased air temperature, carbon dioxide levels, and humidity.

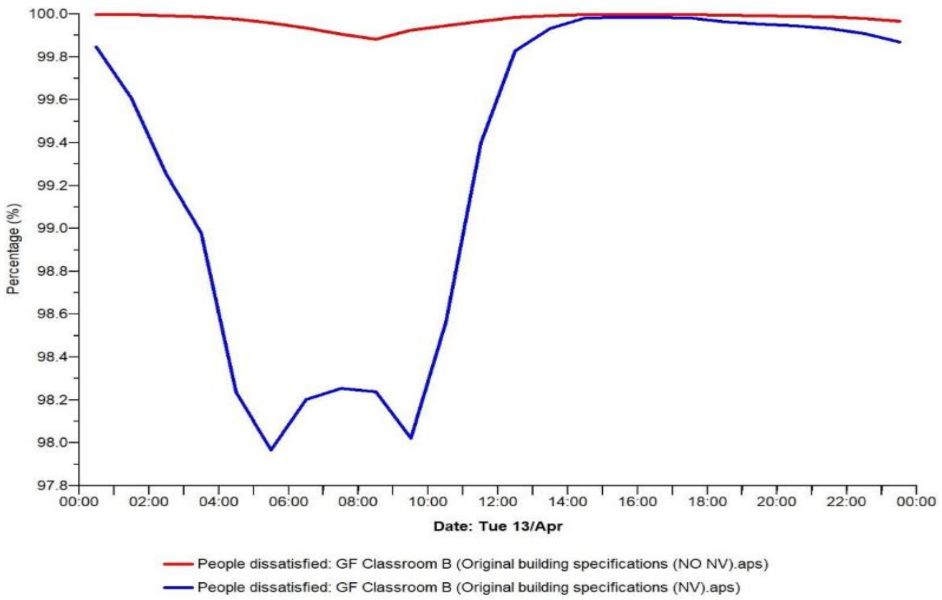

Figure 7-14 A comparison of occupant satisfaction with and without natural ventilation is shown in 'GF Classroom B'.

The findings of satisfaction and corresponding dissatisfaction in Figure 7.14 indicates sufficiency of natural ventilation and this verifies that natural ventilation can foster excellent interior air quality, improve inhabitants' thermal contentment, and elevate the inhabitants' thermal well-being. By opening the building's windows, improved air motion from outside air flows can eliminate the heat that has built up in the building, which is displayed in the graph as lower indoor air temperatures. This consequently decreases the need for mechanical cooling as the interior temperatures are closer to the agreeable temperatures and require less cooling energy to reach the desired comfort.

7.4.3 Building gains

Free cooling is when the external temperature is lower than the internal temperature, there is the potential for free cooling to occur, usually in the evenings when there is no solar radiation, which can be achieved with a mechanical ventilation system or through natural ventilation. Natural ventilation is a passive approach which does not require any energy consumption. If the outdoor air flow rate is sufficient, a convective exchange between the cool, fresh air and the building's fabric can occur. However, introducing natural, free cooling only increases the mean air temperature regardless of the fabric, from Table 7.8, which also indicates that the number of people dissatisfied is directly related to the indoor air temperature.

7.4.4 Free Cooling and Nighttime Purge

High thermal mass materials are most effective when used in conjunction with strategies of night cooling, as it allows the heat stored during the day to be released by creating air movement. The PassivHaus specifications and the previously identified ‘Test 1’ were tested. Tables 7.8 and 7.9 display the effect of night cooling in both the ‘hot’ and ‘dry’ months. The greatest impact of night cooling is seen with the PassivHaus specifications, as it not only has a positive effect during the hottest month, but the mean annual temperature can be reduced by up to 13% in one of the colder months. Despite this, the indoor air temperature remains greater than the other tests, as the day-to-night temperature difference and night-time air velocity are not significant or regular enough to allow heat to be released from the heavily insulated fabric meaningfully.

Table 7.9 Comparison of mean air temperature and mean people dissatisfied for night cooling test during the wet season.

Cooling Test 10th -17th April (Hottest Week of the Year)		
Building Fabric Test	**Mean Air Temperature (°C)**	**Mean People Dissatisfied (%)**
Original Building Specification	37.99	99.82
Original Building Specification (Natural free cooling)	38.68	99.92
Test 1 Specification	37.61	99.37
Test 1 Specification (Natural free cooling)	38.04	99.84
PassivHaus Specification	43.34	100.00
PassivHaus Specification (Natural free cooling)	39.68	99.81

Table 7.10 Comparison of mean air temperature and mean people dissatisfied for night cooling test during the dry season.

Cooling Test 2nd -9th January (Coldest Week of the Year)		
Building Fabric Test	**Mean Air Temperature (°C)**	**Mean People Dissatisfied (%)**
Original Building Specification T1	24.81	11.54
Original building specification (Natural free cooling)	24.15	12.47
Test 1 Specification	24.96	14.76
Test 1 Specification (Natural free cooling)	24.07	11.19
PassivHaus Specification	30.62	62.62
PassivHaus Specification (Natural free cooling)	26.57	34.04

Using natural free cooling, Test 1 is an effective solution. Statistics show that the mean air temperature and the number of dissatisfied people is at least during the month of January. Figures 7-15 and 7-16 demonstrate that Test 1 with natural cooling consistently produces the best results. People are more comfortable when the air temperature is lower.

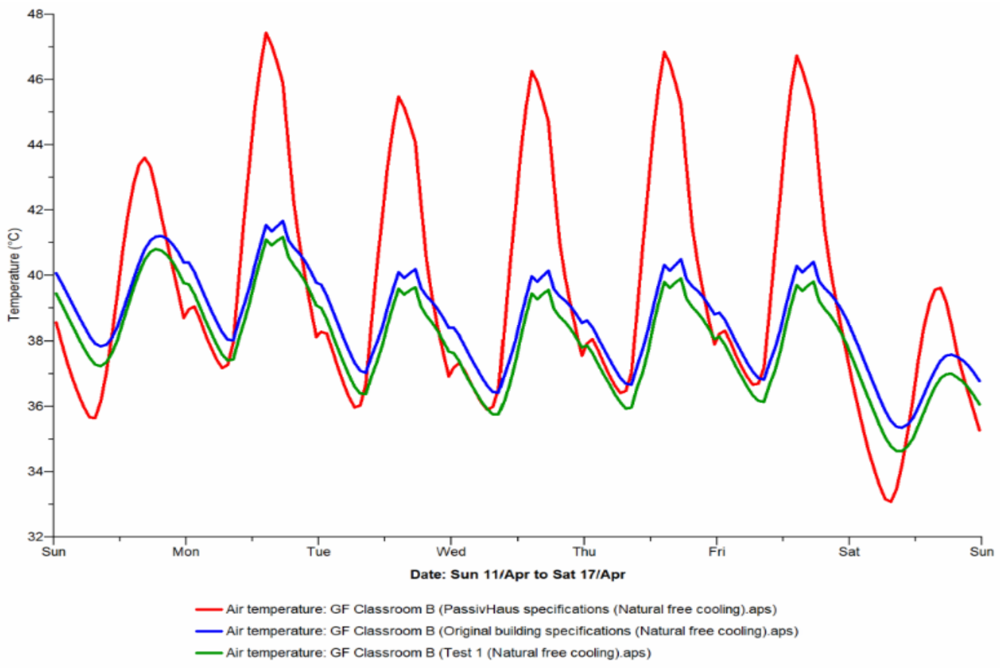

Figure 7-15 Comparison of air temperature; Night cooling test during the wet season.

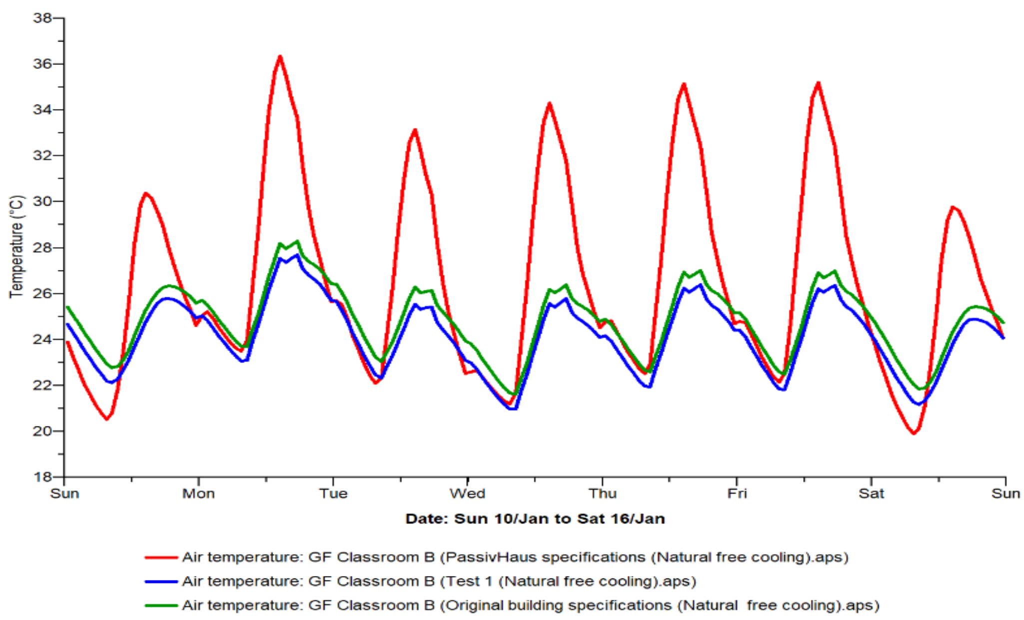

Figure 7-16 Comparison of air temperature for night cooling test during the dry season.

7.4.5 Infiltration and Air Tightness

The graph in Figure 7-17 illustrates how the infiltration rate through 'GF Classroom B' alters when the amount of air changes per hour is modified.

Generally, infiltration is thought of as unintentional and undesirable. But in this case, allowing more drafts to enter the building can decrease the cooling load. Initially, the building has a rate of 0.5 ACH, which can be lowered by making the structure more airtight. It also demonstrates that infiltration results in a net loss of heat, making it impossible to use infiltration to regulate thermal comfort within the building during operating hours. As the infiltration rate decreases, the potential to use infiltration as a source of heat diminishes. Consequently, the indoor air temperature will begin to rise due to the other internal gains, as the air is not being replaced sufficiently.

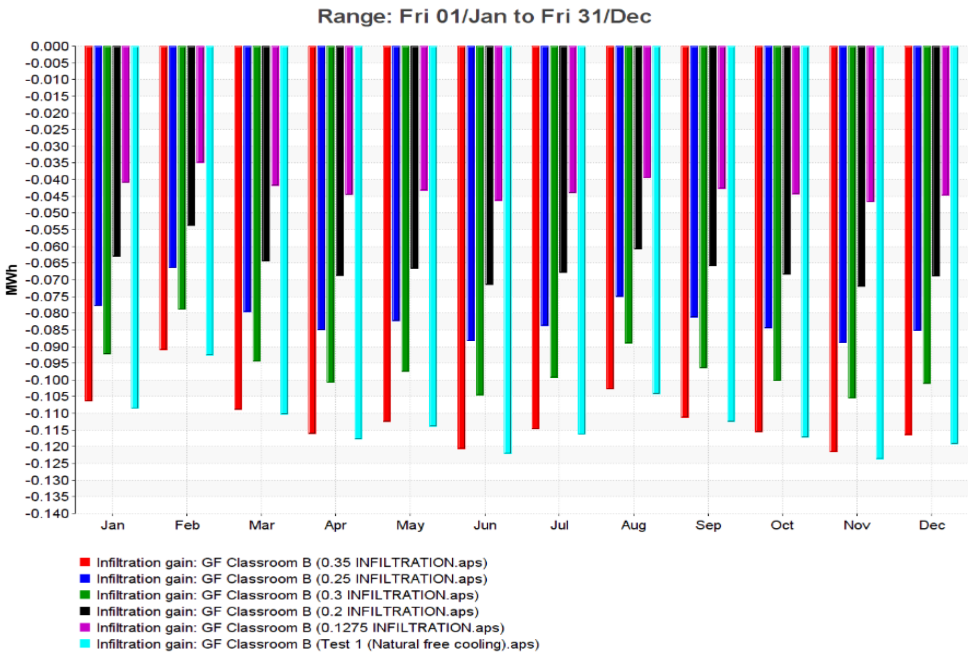

Figure 7-17 Comparison of infiltration gain for infiltration test, shown in 'GF Classroom B'

Fig 6.16 shows that the best infiltration rate is 0.5 ACH, which results in a 9.8% greater infiltration loss than 0.35 ACH in climates like Nigeria. To reduce the amount of outdoor heat entering the building, the volume of air flowing through should be reduced. Since the difference between indoor and outdoor temperatures is very small, the air temperature inside isn't affected much. The increased air changes are only beneficial in providing fresh air and improving air quality. Infiltration isn't a fixed value, but rather is pushed by buoyancy and wind forces, this could be the reason why the building didn't deliver the predicted results (Table 7.10).

Table 7.11 Input data; Mean annual air temperature for each infiltration test.

Var. Name	Location	Filename	Type	Min. Val.	Min. Time	Max. Val.	Max. Time	Mean
Air temperature	GF Classroom B	0.35 INFILTRATION.aps	Temperature (°C)	20.90	07:30,13/Jan	41.70	17:30,28/May	32.12
Air temperature	GF Classroom B	0.25 INFILTRATION.aps	Temperature (°C)	21.04	07:30,13/Jan	41.72	17:30,28/May	32.18
Air temperature	GF Classroom B	0.3 INFILTRATION.aps	Temperature (°C)	20.97	07:30,13/Jan	41.71	17:30,28/May	32.15
Air temperature	GF Classroom B	0.2 INFILTRATION.aps	Temperature (°C)	21.10	08:30,13/Jan	41.73	17:30,28/May	32.21
Air temperature	GF Classroom B	0.1275 INFILTRATION.aps	Temperature (°C)	21.19	08:30,13/Jan	41.74	17:30,28/May	32.25
Air temperature	GF Classroom B	Test 1 (Natural free cooling).a	Temperature (°C)	20.96	07:30,13/Jan	41.72	17:30,28/May	32.16

Figure 7-18 illustrates the correlation between the concentration of CO2 and decision-making skills in a classroom setting. Maintaining a CO2 concentration between 600 ppm and 1000 ppm is most beneficial. Figure 7-19 further illustrates the effect of decreasing the infiltration rate on the CO2 concentration of 'GF Classroom B'.

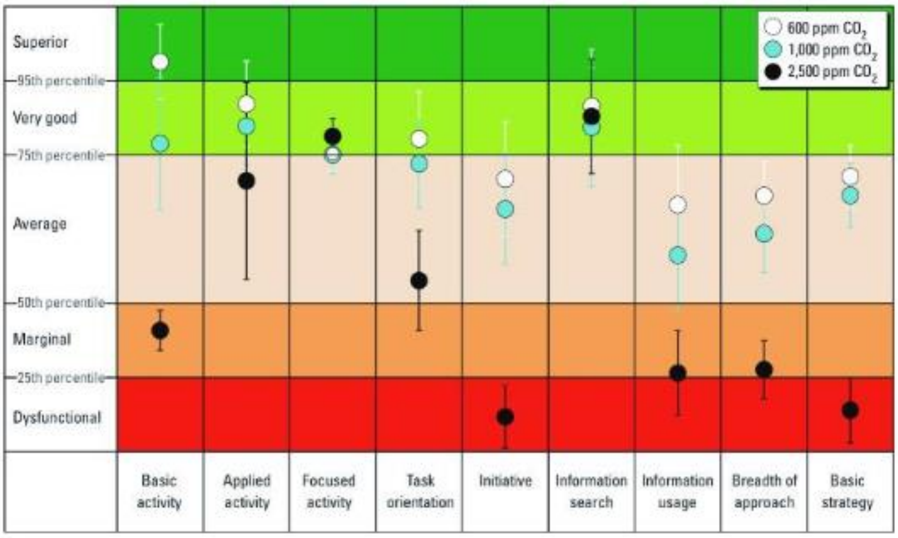

Figure 7-18 Impact of different indoor CO2 concentrations on performance.

According to ASHRAE building standard for ventilation, approved position document, ASHRAE-62, (2022), the average CO2 concentration of less than 1500 ppm is recommended during occupancy hours in a naturally-ventilated teaching space, above is considered hazardous. This is significant when all the infiltration rates tested have met the suggested value.

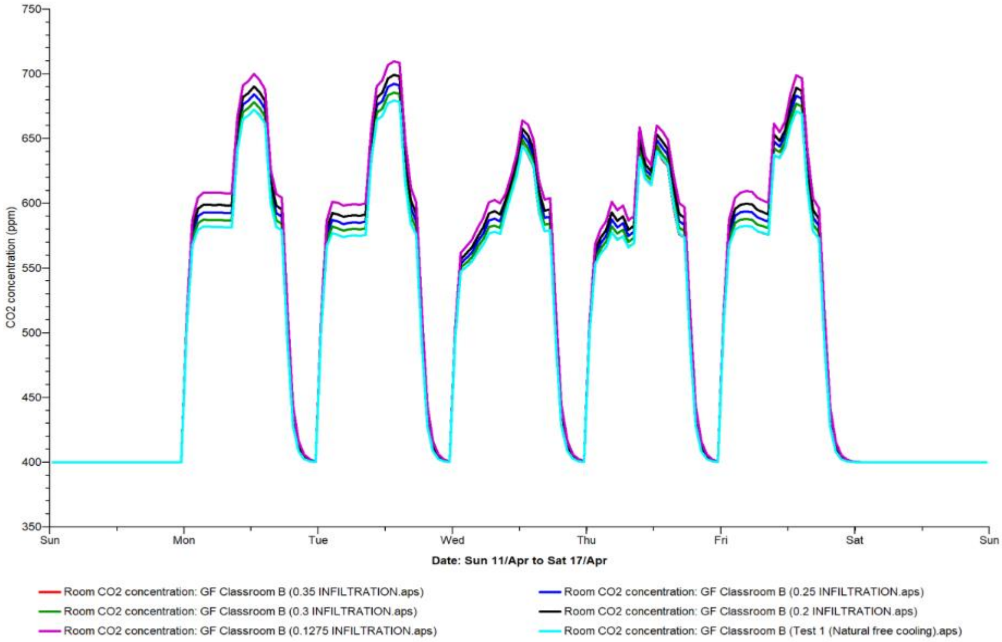

Figure 7-19 Comparison of room CO2 concentration for each infiltration test, shown in 'GF Classroom B'.

Figure 7-20 demonstrates the influence of different infiltration rates on the number of dissatisfied occupants. It was found that the lowest CO2 concentration and highest infiltration rate of 0.5 ACH produced the most comfortable position to occupants. While increasing the air tightness of the building had a limited effect on occupant comfort, there was a reduction of 1.5% in dissatisfied occupants and a decrease of 0.04°C in the mean annual air temperature when the air changes decreased to 0.35 ACH. Therefore, to optimize the model, this test will be enforced as it had a more positive effect on the indoor temperature than on the CO2 concentration and the percentage of people dissatisfied.

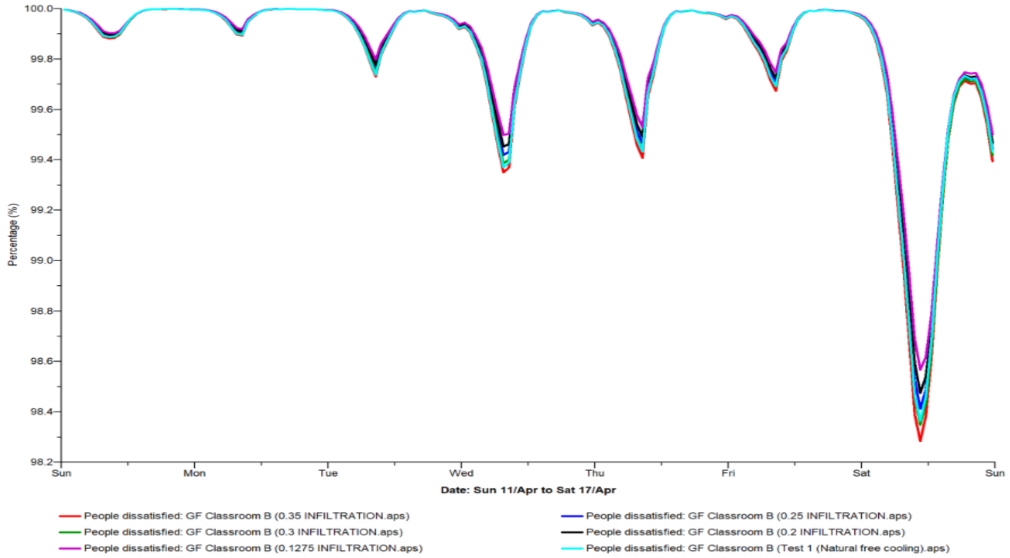

Figure 7-20 Comparison of people dissatisfied for each infiltration test, shown in 'GF Classroom B'.

7.4.6 Glazing adjustment.

Figure 7-21, the effect of introducing insulation to the windows of Ground Floor Classroom B, which has many windows, is shown. In contrast to the increase in thermal mass that caused undesirable heat retention, the double and triple glazing did not have this effect.

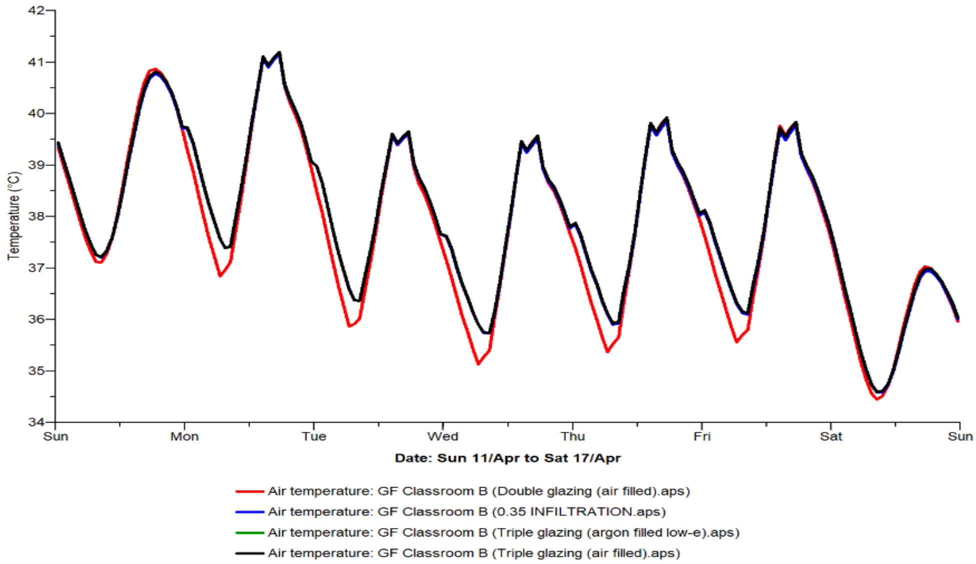

Figure 7-21 Comparison of air temperature for different glazing tests.

The figure illustrates double glazing with an air cavity as the most successful option that would lower the minimum air temperature from midnight to 10 am. This could help to pre-cool the room, so it is comfortable for people when they arrive.

The indices shown in Figure 7-22 demonstrate the reduction in solar gain that can be achieved by implementing air-filled double glazing. The study found that during the week, from 7:00 am to 6:00 pm, solar gain was reduced by up to 17%. This optimization resulted in an annual reduction of solar gain from 2.18 MWh to 1.84 MWh, which in turn led to a decrease in the interior air temperature and the demand for cooling.

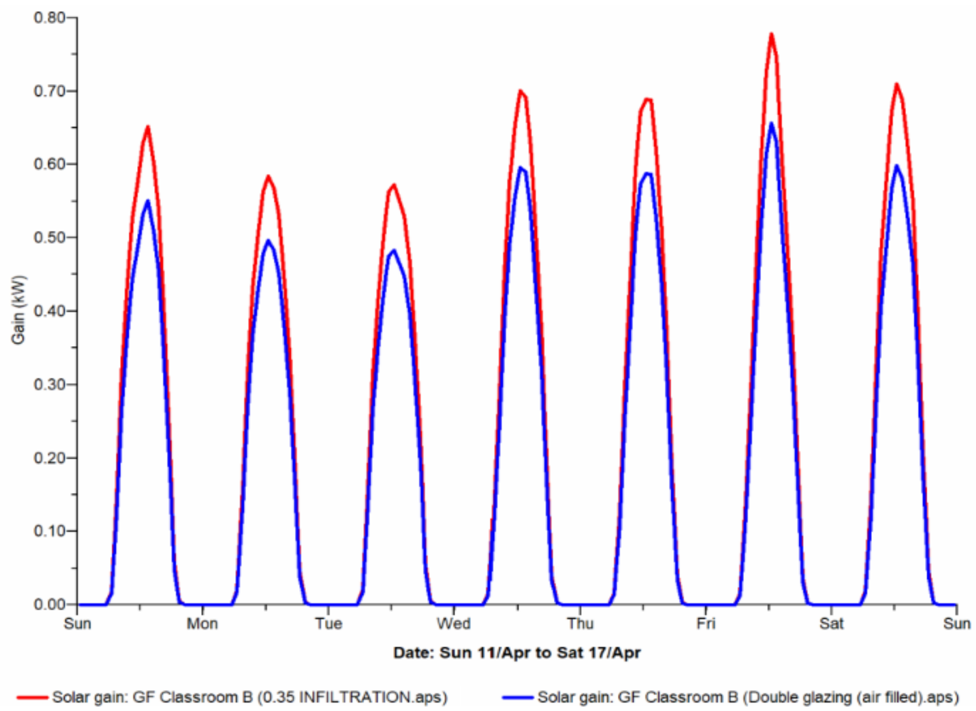

Figure 7-22 Comparison of solar gains between most effective glazing.

The double glazing serves as an insulation layer, blocking conductive heat transfer and keeping the space cooler during the warmest months. But if the insulation is increased to the point of excessive thermal mass, heat is absorbed and trapped within the building, which results in no further benefit.

7.4.7 Shading projections

The SunCast diagrams in Figure 7-23 indicate that both the north and south facades of the building receive the same solar radiation due to the sun's path over the course of the year, which means the same type of overhead shading can be implemented.

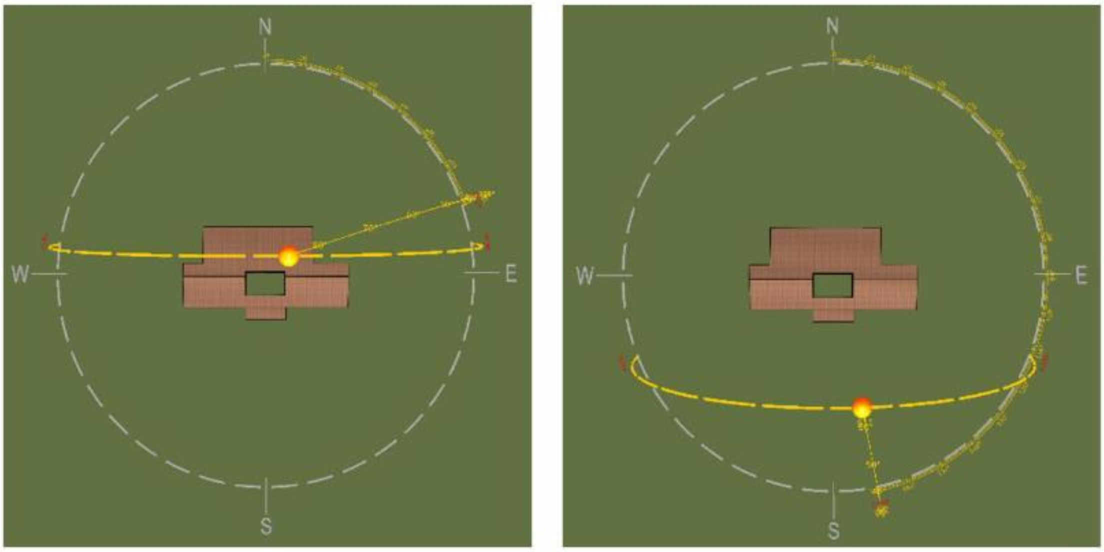

Figure 7-23 SunCast diagrams of the original building: cold/wet season (left), and hot/dry season (right).

Table 7.11 demonstrates the effect of shading on the daylight factor in 'GF Classroom B', with the percentage of daylight below the 300-lux threshold and daylight factor weighted average of 1.6% below the recommended minimum of 4.5%, decreasing with the addition of shading device.

Table 7.12 Effect of shading projections on lighting

Test Iteration	(%) Daylight above threshold	(%) Daylight factor. Area-weighted average	Illuminance (Lux) Area-weighted average
No shading	92.4	1.6	196.594
0.5m Shading Projections	59.2	1.0	77.135
1m shading projection	52.1	0.6	46.789

To ensure occupant satisfaction and energy efficiency, the learning space must remain bright and daylit, as artificial lighting creates internal gains that add to the cooling load. Natural daylighting is thus of utmost importance. It is essential to select appropriate shading material, since it will affect the amount of solar radiation that is absorbed, transmitted, and reflected.

The air temperature for different shading tests is presented in Figure 7-24, and it was seen that the maximum air temperature was reduced by 0.05°C with the addition of a meter of overhead shading. This effect was observed for both the minimum and maximum temperatures, showing that the material chosen for the overhead shading had a positive, albeit slight, effect on the building, by redirecting radiation away from the building fabric.

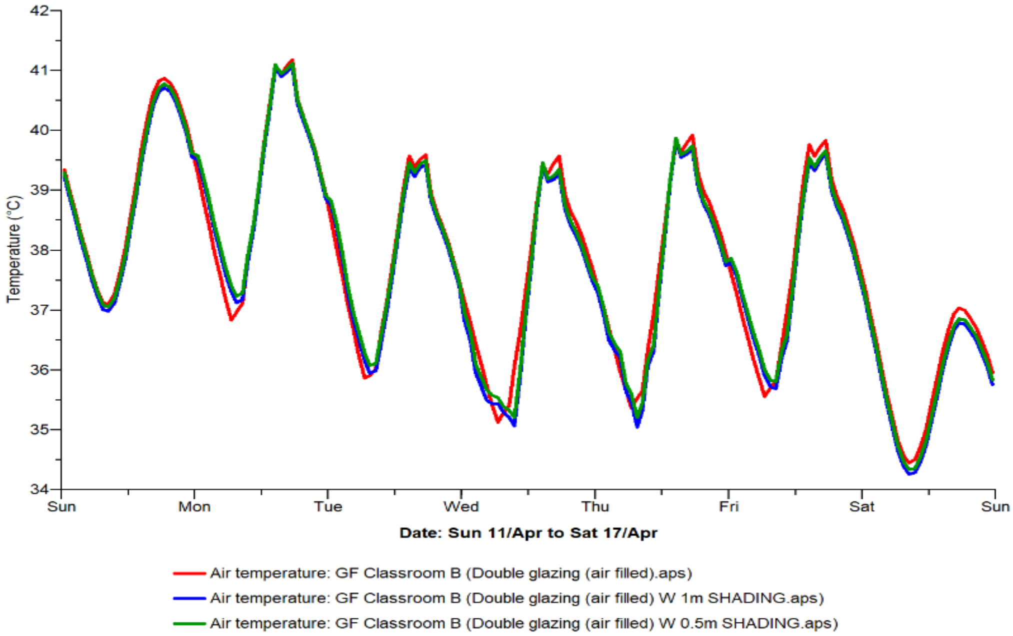

Figure 7-24 Comparison of mean annual air temperature for different shading projections.

7.4.8 Vegetation Shading

Using trees to shade the north and south facades of the building and the central courtyard was explored, however, the IESVE software could not accurately show the potential for evapotranspiration. Table 7.12 and 7.13 showed that the introduction of these trees led to a minimum benefit in conduction gain and even in increased air temperature. This could be due to the trees blocking any breezes or winds. Even though the simulation results did not reflect the potential for evapotranspiration, they could have contributed to cooling the environment and the building. It appears that introducing vegetation only blocks the room's access to daylight and adversely affects the occupants, so this design change will not be continued in further simulations.

Table 7.13 Comparison of internal conduction gains with/without vegetation.

Var. Name	Location	Filename	Type	Min. Val.	Min. Time	Max. Val.	Max. Time	Mean
Internal conduction gain	GF Classroom B	Vegetation shading.aps	Gain (kW)	-2.7977	14:30,21/Jul	3.3257	07:30,25/Dec	0.4692
Internal conduction gain	GF Classroom B	Double glazing (air filled) W	Gain (kW)	-2.7972	14:30,21/Jul	3.3606	07:30,25/Dec	0.4945

Table 7.14 Comparison of air temperature with and without vegetation.

Var. Name	Location	Filename	Type	Min. Val.	Min. Time	Max. Val.	Max. Time	Mean
Air temperature	GF Classroom B	Vegetation shading.a	Temperature (°C)	20.62	07:30,13/Jan	41.61	17:30,28/May	31.92
Air temperature	GF Classroom B	Double glazing (air fill	Temperature (°C)	20.51	07:30,13/Jan	41.51	17:30,28/May	31.81

7.4.9 Roof Canopy Shading

The energy efficiency of the corrugated Alluminium sheet with its high solar reflectance was used for roof shading (Figure 7.11). Figures 7-25 and 7-26, with Table 6.14, show the effects on fabric gains through the north-facing roof slope. Introducing the shade led to a 64% increase in external conduction losses but at the same time a 95% rise in total internal conduction gains. This means that less outdoor heat is absorbed into the building, less heat is retained within the building, and less heat is released through the roof. A separation between the sunshade material and the roof permits rapid disbursement of heat. The airflow rapidly dissipates radiation which has gone through the shade, diminishing external gains. This was demonstrated in Figure 7-25, where external conduction losses are continually higher than when there is no shade in position for each month of the year. The gap should also provide an avenue for removing heat which is leaving through the cloth. However, this is not the case, as the internal gains have augmented with the sunshade. This could be because the double skin system is composed of a highly insulating lower layer. If there is no air movement between the canopy and the roof of the building, the captured heat may get absorbed and held in the building material.

Table 7.15 Comparison of heat transfer through the fabric, in 'Roof Slope 1'.

Simulation Test	Annual external conduction gains	Annual internal conduction gains
Double glazing (air filled) with 1m shading.	-2.8633	-0.8160
Roof Decking	-4.7024	-0.0357

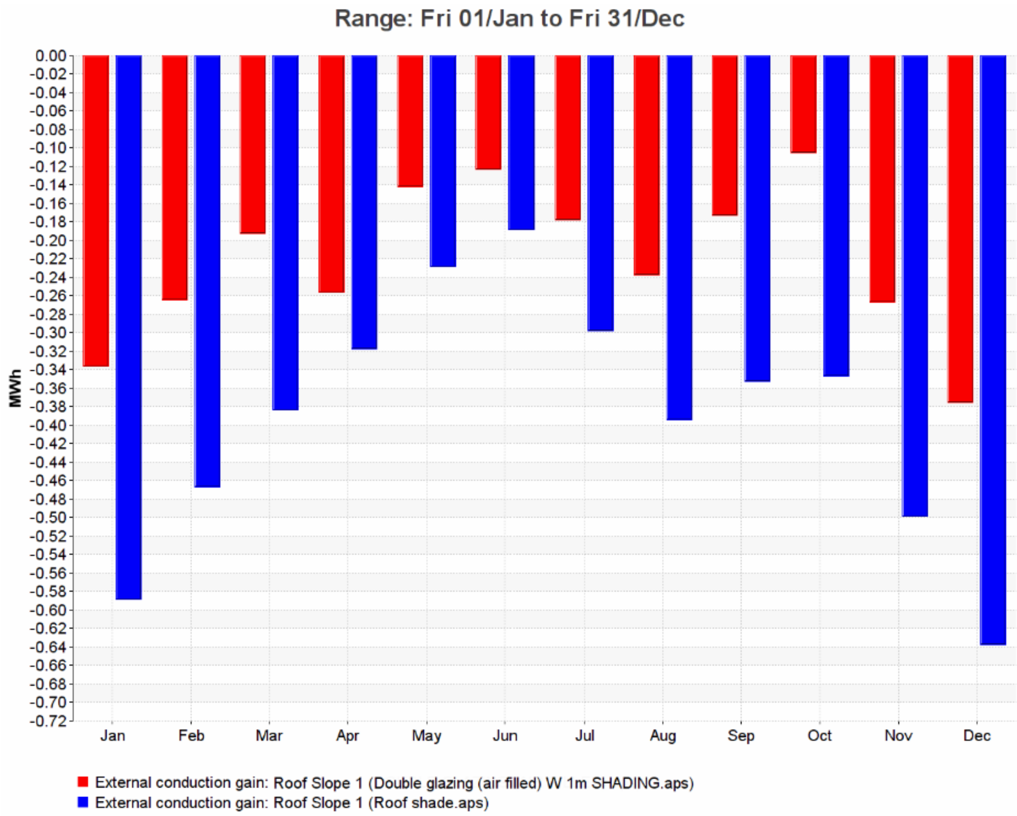

Figure 7-25 Monthly external conduction gains with and without the roof shade, 'Roof Slope 1

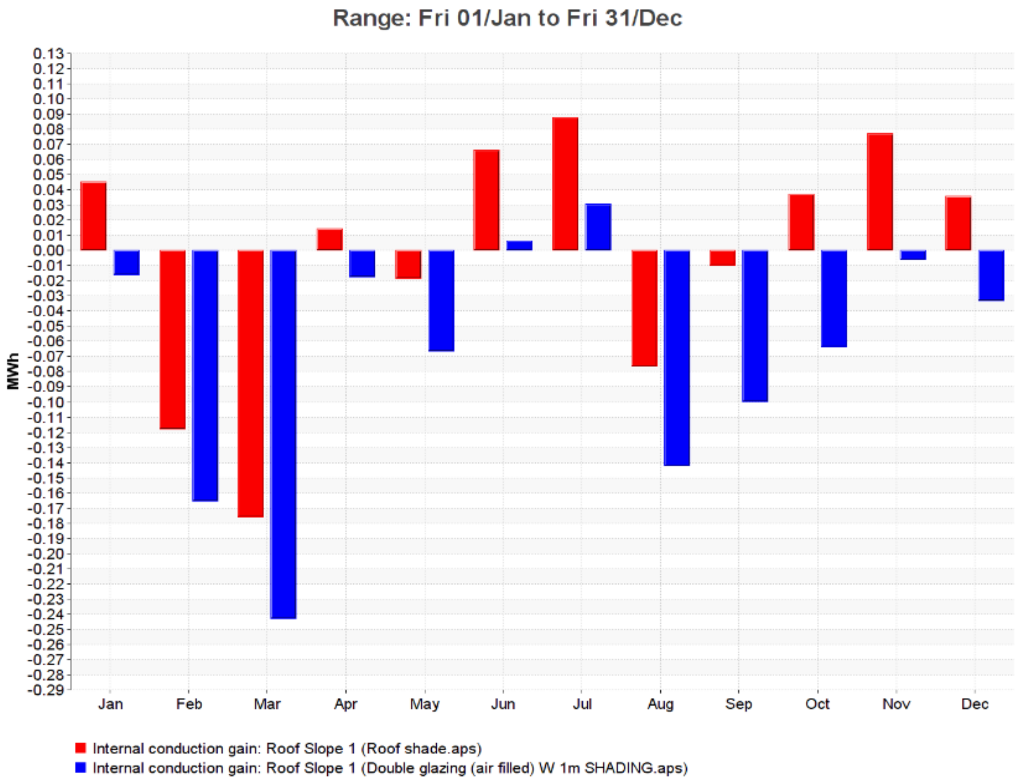

Figure 7-26 Monthly internal conduction gains with and without the roof shade, 'Roof Slope 1'.

Figures 7-25 and 7-26 indicate that the addition of the roof shading had an impact on the air temperature of GF Classroom B and Classroom at first floor (FF) level. It was expected that the first-floor room would be impacted more with heat, as it is located directly beneath the roof shade. Throughout the week, the temperatures in both rooms behaved slightly differently, showing an advantage of having the shade. The minimum and maximum air temperatures of both rooms at GF and FF increased. This instance may be due to the roof canopy restricting the amount of heat flow escaping from the building, leading to an increase in internal temperatures.

Figure 7-27 and 7-28 presents a comparisons of air temperature with and without roof change highlighting the impact of outdoor airflow rate, and reflecting the insufficiency of air movement to create ventilation through the double-skin roof system and dissipate the heat via convection.

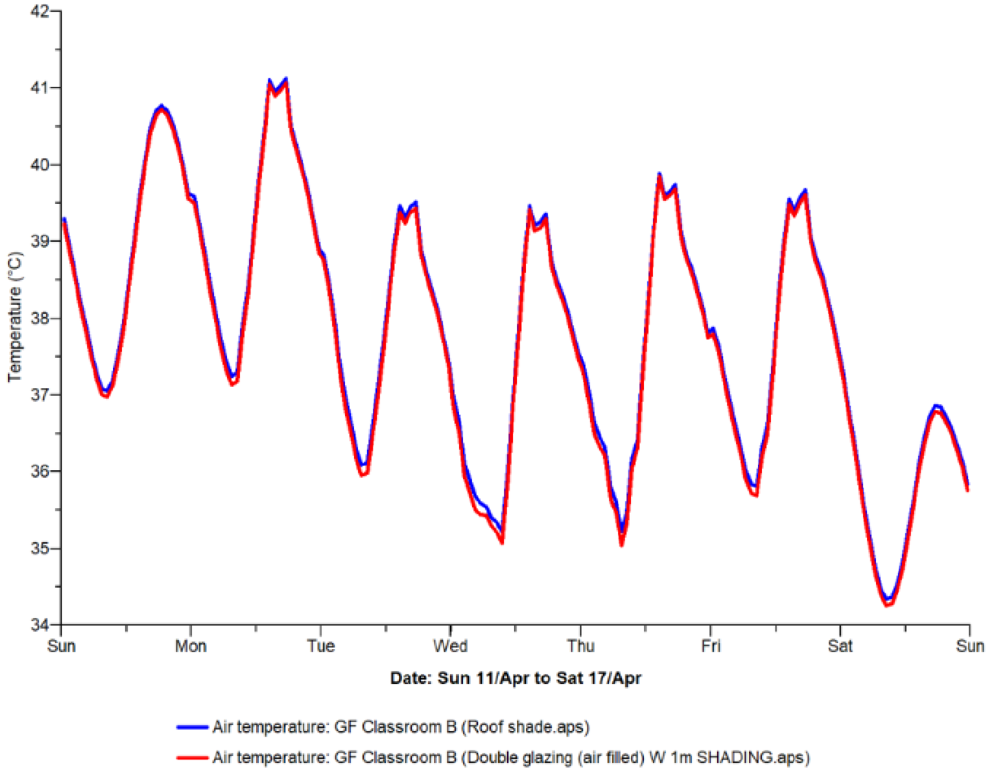

Figure 7-27 Comparison of air temperature with and without the roof shade.

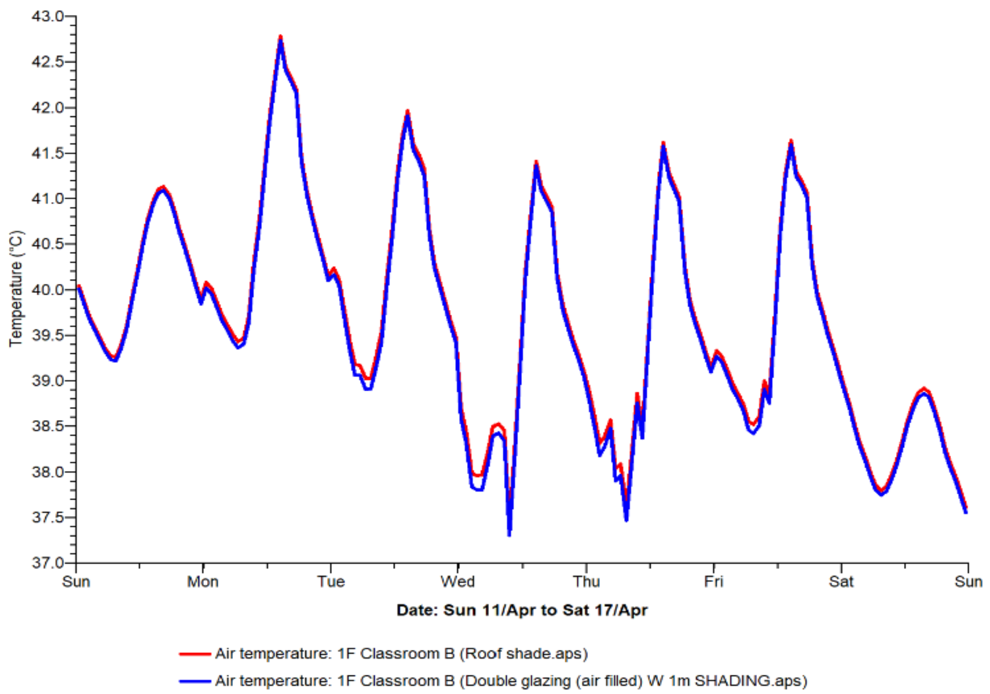

Figure 7-28 Comparison of air temperature with and without the roof shade.

7.4.10 Solar power potential

By mounting solar panels on the roof in an appropriate orientation, they can be used to generate renewable energy while also providing passive shade to help keep the building cool. An additional air gap is included between the panels and the roof canopy to ensure the panels remain at a relatively low temperature and remain effective in capturing energy from the sun. Figure 7-29 illustrated that the solar panels produce a considerable amount of shading of the roof. This effect is notably beneficial in Nigeria's dry season (March-June), when humidity is low, temperatures are high, and solar radiation is at its highest. This additional shading is shown to increase the mean annual heat loss through the roof fabric by 531%, from 0.0357 MWh to 0.2253 MWh.

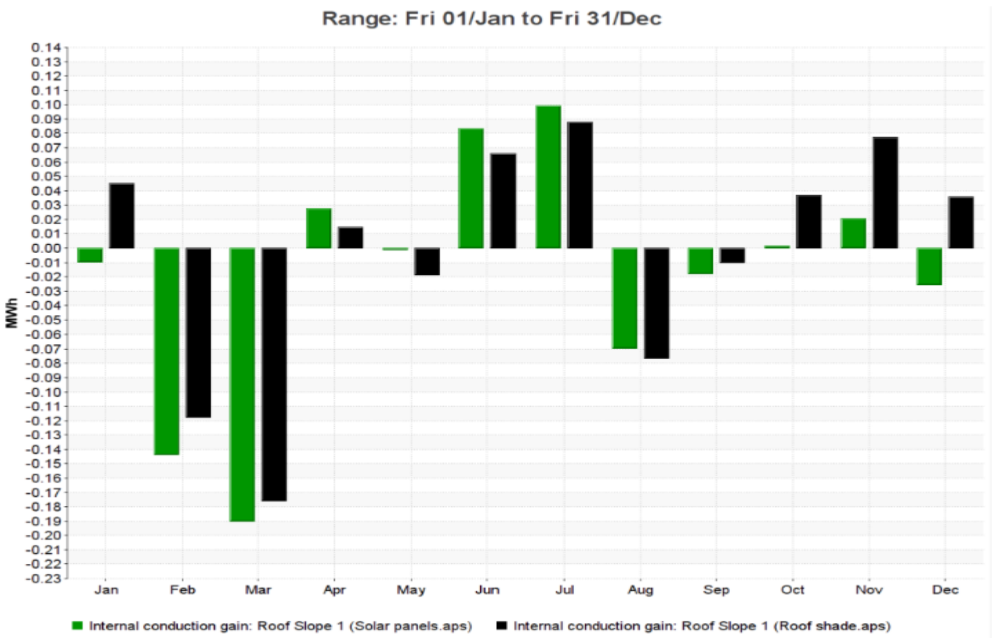

Figure 7-29 Comparison of internal conduction gains through 'Roof Slope 1', with and without solar panel shading.

Figure 7-30 below, displays the amount of PV electricity that could be generated with the set-up of PV panels shown in Figure 19. The PV panels were placed horizontally to absorb the most energy year-round. The equator is the most effective spot for solar energy since the sun's heat and light are spread evenly there. Ultimately, the total PV electricity generated annually is 212.58 MWh.

Many global research prescribed integration of solar panels as an alternative and efficient way to increase building energy and performances. (Attah & Idowu, 2017; Korsavi et al., 2018; and Tawil et al., 2021).

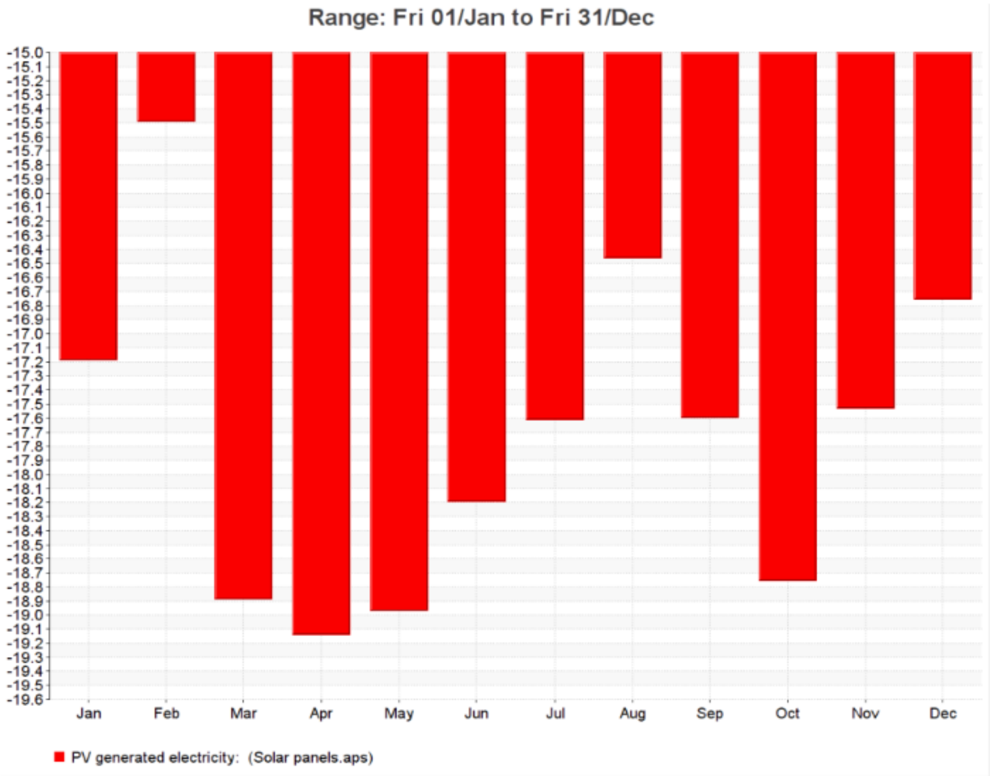

Figure 7-30 Potential PV generated electricity annually using solar panels.

7.4.11 Impact of Passive Cooling Strategies on Cooling Load

Table 7.15 illustrates numerically the impact every alteration to the design had on the building's possible cooling load. Throughout the evaluation of the passive approaches, 8-parametric results processes were observed, and differences were compared with the original building load/values.

Table 7.16 The monthly reduction in total cooling plant sensible load after the iterative change

S/no	**Parametric Tests**	**Total Room Cooling Plant Sensible Load (MWh)**
1	Original Building	332.90
2	Natural Ventilation	370.93
3	Fabric U-Value	330.25
4	Free Cooling	330..25
5	Infiltration & Air Tightness	329.96
6	Glazing G-Value	329.75
7	Shading Projection	328.15
8	Roof Canopy Shading	326.62
9	Solar Panel Shading	327.57

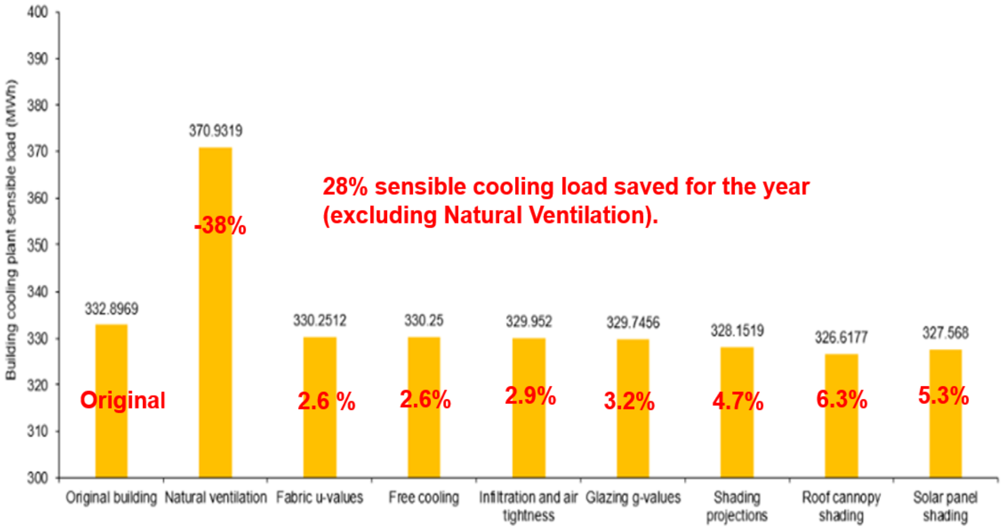

Figure 7-31 Reduction in total building cooling plant sensible load after each iterative design change.

The data from Table 7.15 and Figure 7-31 implies that examining the connection between air temperature and fabric (elements) gains does not provide the desired lasting solution for achieving assessment and provision of the cooling load for each passive cooling strategy. The total room cooling plant sensible load is calculated in megawatt hours (MWh), and comparisons are made with evaluation from the original building fabric (332.90MWh) values across each parametric test to obtain the differences less reduction in cooling load was achieved in each passive iteration test, only for ventilation. The least among the tests is a 2.6% reduction in fabric u-value when the building is freely cooled. Roof canopy shading offers the highest reduction of 6.3%, followed by solar panel shading with 5.3% and 4.7% window shading projections. This demonstrates the effectiveness of the shading strategy in the climate. Glazing at a middle proportion reduces the cooling load by 3.2%. The simulation calculating the cooling load does not consider night purging (Table 7.15 and Figure 7-31). This was tested by only using natural, free cooling (MacroFlo app) with no temperature setpoint, and this does not guarantee cooling load to be calculated because the results are the same as in the previous step. This process's advantage is visible in reducing indoor air temperature.

The introduction of natural ventilation caused an 11.4% increase in the cooling load. This was due to the drop in air temperature at night when the windows were shut and the need to remove more heat the next day when they opened again. This could be avoided by changing the Windows opening settings. When there is sufficient air movement, a breeze can be brought inside; however, when the wind pressure is low, the space only becomes warmer with hot, humid air. Although adding natural ventilation augmented the cooling load, it might be helpful to investigate adjusting the opening times as a potential solution. Air circulation has a positive effect on occupants' satisfaction by evaporating perspiration and creating a more comfortable environment (Bughio et al., 2020; Lau et al., 2019; Odunfa et al., 2018). The people in the building seemed to be much more content during the occupancy hours of a naturally ventilated building. The next alteration of roof insulation had the greatest effect on the cooling load, reducing it by 6.3%. The roof's insulation kept the internal temperature more consistent, thus decreasing the need for mechanical cooling. The other changes, up to and including the addition of the roof canopy, had a less noticeable impact but still had a beneficial effect in cutting down on mechanical cooling.

7.5. Summary

The simulation results indicated that implementing passive cooling changes had limited effects on the cooling load of the building analysed. However, these changes effectively decreased heat gain and sun exposure, ultimately improving the comfort of those within. This research highlights the potential of passive cooling in hot climates. By utilising IESVE software, this simulation process can efficiently determine the effectiveness of passive cooling in different climates, leading to more sustainable and practical cooling solutions. Available passive strategies led to a 28% reduction in cooling load. The simulation assessed the daylight factor for lighting efficiency, showing the building's performance was below the minimum standard with a 1.6% DLF. The daylight continued to diminish with the addition of shading devices. Adequate daylighting is crucial in classrooms, influencing a building's energy efficiency and performance. The South African building regulation SANS 10400-XA (2011), suggests an annual cooling load below 241.34 MWh for educational buildings. However, the 212.58MWh generated from renewable (PV) integration in this study is within the minimum of the earlier regulation. This further highlighted the need to integrate renewable energy into the Nigerian physical infrastructure. This research section utilised IESVE software to evaluate passive cooling techniques within Nigeria's hot and dry climate. It analyses the impact of climatic factors and applies passive strategies to provide solutions for reducing cooling load, occupant discomfort, and solar radiation in the university building. Furthermore, it proposes the integration of renewable energy as an alternative to the electricity grid, concerning meeting the required cooling load and improving indoor environmental quality for students' and staff's comfort, health, and well-being.

CHAPTER EIGHT

8. CONCLUSIONS AND FURTHER WORK

8.1 Introduction

This chapter synthesised the conclusions from various study chapters by providing recommendations for future research in Thermal comfort, Building performance assessment and energy efficiency for sustainable development in Nigeria's Hot/dry climate. It generalised how the research objectives were achieved in the context.

8.2 General Conclusion and Recommendations

Buildings in tropical climates often underperform due to the impact of climate change, particularly overheating, which causes discomfort and serious issues for occupants. Nigerian Universities face challenges due to climate change phenomena, poor design and construction techniques and factors that mechanical cooling devices cannot resolve. Electricity is expensive and unsustainable, and natural ventilation should be emphasised in the design of university facilities to reduce energy demand. Applications of passive and energy-efficient design approaches in hot/dry climates also allow for possible retrofitting of existing buildings in Nigeria. Tertiary institutions globally play a crucial role in providing quality education, offering spaces for learning, administration, and utilities, hence the need for comfort to the occupants. Towards providing conducive learning, this research has intensified the need to explore viable climate-responsive design alternatives that suit the climatic conditions.

Considering this precedence, this research examined ways of improving thermal comfort and energy efficiency in response to climate considerations and for parameters typical of university buildings in the hot/dry town of Birnin Kebbi, Nigeria. The following objectives further sustained the considered study aim:

i. To conduct a thorough literature review and use open-source data and knowledge to study sustainable building design practices and processes of tropical hot/dry climates.

In conclusion, the introduction of the research objectives on assessing thermal performance and energy efficiency in Nigerian university buildings within a hot/dry climate set a determined target of improving the performance and efficiency of the facilities by utilising an effective passive strategy to address sustainability needs in this region, with clear objectives outlined, it highlights the significant research gap to refill in the study, offering novel insights into Nigerian university infrastructure. Understanding the historical development of these buildings through literature review was considered vital for the effective adoption of the methodology of building assessment; the chosen methodologies were, however, concluded to be well-suited to the objectives, positioning the study to contribute to sustainable building practices in Nigeria's hot/dry climate.

It's evident from the research that many techniques of passive strategies and principles are diverse and used in respective climates. The method taps from the endowment of natural climatic elements and natural elements of the climate to create energy-efficient, environmentally friendly, and comfortable buildings, as reviewed in Chapter 2 of this research. The harsh Hot/dry climate conditions in Birnin Kebbi that challenge human comfort and energy consumption in Nigeria can be mitigated by implementing techniques such as proper orientation, shading devices, thermal mass, natural ventilation, and efficient insulation.

To enhance sustainable architecture development in Nigeria's hot and dry climate, incorporating passive design techniques is crucial; these techniques reduce the need for mechanical cooling and heating systems, leading to significant energy savings and a reduced carbon footprint. ASHRAE-55 Standard and others related were used as reference minimum guide. This aligns with global efforts to combat climate change and promote sustainable development. Passive design improves living conditions and building longevity and offers economic benefits through reduced energy. Application of passive design techniques in building infrastructure will unlocks the full potential of sustainable architecture in Nigeria's hot and dry climate, creating a responsive and resilient built environment.

ii. To evaluate the selected case study buildings on the overheating phenomenon on climatic variables, such as temperature, humidity, carbon dioxide (CO2) and ventilation levels, towards providing an IEQ minimum standard for occupant comfort, health, and well-being.

The analysis of thermal comfort perception among occupants in the Architectural studio and classroom complex has yielded valuable insights into how seasonal variations and environmental factors impact their comfort levels. The research questions posed in this study have provided a comprehensive understanding of these dynamics. Subjective views in chapters 4 and 5 of the questionnaires scrutinise the thermal comfort variables of the indoor environment in the two learning environments despite the occupancy and form differences. Additionally, chapter 4 and 5 in the study provided a foundation for assessing thermal performance and energy efficiency in pursuit of a higher quality environment and sustainable building development in the climatic region. Experimental monitoring of the case study building using NETATMO data logger and associated sensors. This allowed for quantification of indoor environmental quality (IEQ), thermal comfort and occupants' adaptation to the heat beyond the IPCC minimum standard and recommended temperature of 26°C for educational buildings. The findings highlight the learning environment's higher minimum and maximum SET and comfort temperatures.

In the earlier discussion (chapter 2) that guided on measuring environmental factors, it was discovered that solar radiation was causing an increase in temperature within the interior classrooms/studios. To improve thermal comfort, it is recommended to shade the large, framed windows that allow solar radiation to enter the building during summer, causing overheating. Additionally, students can access electrical cooling devices such as fans and air conditioning units, but implementing a control regime to turn them on and off as needed is suggested. It was discovered that many fans and ACs are left running when not required, contributing to unnecessary energy consumption. Regarding lighting comfort, the studio complex windows are not shaded from direct sunlight and lack external or internal shading elements like curtains or blinds. Adding these elements can help reduce overheating and health hazards caused by intense solar radiation. Furthermore, the studios receive abundant natural light, unlike classrooms and harnessing natural lighting and controlling it properly to avoid the unnecessary use of artificial lighting during class hours is suggested. To save energy, intensifying control measures for artificial lighting and offering that windows can be blinded off without affecting indoor illumination is recommended.

iii. To demonstrate the retrofitting and maintenance framework for upgrading existing university buildings to achieve thermal performance and energy efficiency standards and integrate renewable energy (photovoltaic) systems into the building envelope.

The objective evaluation of the building with data loggers and experimental monitoring of the case study buildings using data loggers and associated sensors were able to quantify indoor environmental quality (IEQ) and thermal comfort. This helped occupants adapt to new thermal comfort temperature setpoints calculated to achieve minimum standards. Each learning space's recommended temperature and SET were achieved for the hottest and coldest months of the year. The comfort temperature for occupants in the studio and classroom building for operations is within the range of 29.5°C-29.1°C. There are variations in indices of comfort for studios and classroom complexes. While classrooms performed better with reduced overheating in indoor spaces and lower air temperature, humidity, and carbon dioxide levels in room spaces over the seasons, the Studio complex had poor orientation and absence of shading devices to the exposed windows, leading to increased discomfort for occupants. The minimum comfort provision for occupants of the facilities was achieved for educational buildings in Nigeria's hot/dry climatic zone.

iv. To evaluate the case study buildings on thermal performance, IEQ, and energy efficiency through the parametric process using validated IESVE software and effective computer modelling processes.

Using IESVE software in the simulation process of the two case-studied buildings effectively determines the proficiency of thermal comfort, natural lighting efficiency, building performance, and passive cooling processes in improving the IEQ of the learning environments. The studio complex's Daylight Factor (DLF) is 4.6%, and illuminance levels of 563 Lux were recorded; these values are within the standard guide. In contrast, the daylight factor for lighting efficiency in the classroom complex shows that the building's performance was below the minimum standard with a 1.6% DLF. As reported in Chapters 6 and 7, the daylight continued to diminish with the addition of shading devices. Further research is necessary to evaluate buildings' energy efficiency and performance in different Nigerian climatic zones.

The Nigerian Building Code and BEE Guideline document recommended incorporating passive cooling techniques and computer modeling software to advance sustainable analysis of indoor environmental quality, health, and well-being of occupants in various building types and educational buildings for efficient mitigation (assessment and evaluation) strategies deployed in sustainable integrated design. This research achieved this through a passive maintenance framework for IEQ, comfort, and energy efficiency.

The shading device was designed and accomplished in the VE software as part of fabric maintenance and retrofitting framework. A horizontal shading extension of 0.75 meters effectively controlled solar insolation and lighting to meet the minimum standard. Roof shading was also effective in providing shading and support for renewable energy infrastructure integration.

- The parametric process on the studio building offers a sustainable building performance improvement by utilising renewable energy from the 184MWh photo-voltaic (PV) installation for electricity generation. The building's orientation is challenging, but applying passive techniques reduced the cooling load by 32%. The task accomplished in Chapter 6 demonstrates a promising sustainable energy generation and process solution.

- The combined passive iterations and changes in the building form, excluding natural ventilation, decreased energy consumption for cooling by approximately 28% in the classroom complex. It is recommended that while the impact of individual passive design strategies is limited, they should be complemented with active renewable energy photovoltaic (PV) installation that is demonstrated to provide 212.58MWh of electricity generation, with potential upgrades for further energy performance enhancement.

The building simulation results also indicate that while passive cooling techniques have a limited effect on reducing the cooling load of the buildings evaluated, the increase in heat gain was due to the building's persistent exposure to direct sunlight, leading to increased occupant discomfort. The potential application of passive cooling techniques on buildings in hot and dry climates sets a sustainable building performance target, achieved through multiple evaluation methods and processes.

Further research is necessary to evaluate buildings' energy efficiency and performance and carry out electricity upgrades to support the campus facilities in different Nigerian climatic zones by embracing renewable energy options in Nigeria's climate.

v. To develop recommendations for policy and building design guidelines based on research findings toward promoting the construction of energy-efficient and environmentally sustainable university buildings in the Nigerian climate.

Effective recommendations for improving IEQ and design guidelines are subdivided into three categories: policymakers, building managers/designers, and scholars/academics.

- **Recommendations to Government:** The building standards in Nigeria's National Building Codes and BEE guideline documents have a limited scope, which does not cover all aspects of IEQ. To ensure that minimum standards are met, the minimum window-to-wall ratio (WWR) should be within the range of 0.24 to 0.30 to avoid overheating. Additionally, learning spaces should have a lux value of 300-5500lux and a Daylight factor of not less than 4.5%. To comply with the minimum ASHRAE standard 90.1, the NNBC and BEE guidelines should be reviewed. The international lighting threshold standard in buildings of hot/dry climates, especially in learning environments, should be standardised to prevent indoor heating and reduce the risk of heat stress for occupants.
- It is important to encourage professionals in the construction industry to express their expertise freely and follow codes of conduct to produce quality designs and maintain existing structures. Built-environment professionals should ensure that occupancy ratio guidelines are applied uniformly in designing spaces, design buildings that are sensitive to climate, and adopt passive design and construction methodologies that can help reduce discomfort due to overheating in hot climates. The significance of properly shading windows is highlighted due to the poor orientation of the studio complex discussed in Chapter 6, where a depth of 0.5 meters is recommended based on the simulated tests values.
- The budgetary allocations for higher institutions have been reported as inadequate and inconsistent. This may be due to the increased number of students enrolment, a shortage of learning spaces, and cases of misappropriation and misapplication of funds. As suggested in Chapter 1, the government should increase funding and create special grants for the procurement and integration of renewable energy into public institutions across the country. This will help support the large infrastructure with electricity.
- **Recommendations to Building Professionals:** Building professionals should follow specific temperature benchmarks to ensure thermal comfort in the similar studio and classroom complex. The standard effective temperature (SET) should be between 27.0ºC and 32.0°C, with

a comfort temperature range of 29.1°C to 29.5°C. These two temperature ranges are higher than the CIBSE and ASHRAE guideline minimum provision of 26ºC for educational facilities. as outlined in Chapters 4 and 5. Building managers and designers can use this information to calculate, maintain, and enhance the IEQ of a building for occupant comfort. However, due to the region's scarcity of electrical power supply, passive processes remain an effective strategy. This was observed from the survey findings.

- It is crucial for architects and designers, to deeply understand various methods of assessment of buildings both at pre-design and post-design stages. It is important to focus on designing for occupant comfort rather than just aesthetics. To achieve this, using Building Information Modeling (BIM) applications for simulation during the initial design stage helps in detecting errors and generating sustainable options before actualizing design and construction implementation. There are various software options available in the market to facilitate these tasks of parametric analysis that offer solutions. Furthermore, these tools can also be used to retrofit existing buildings that require maintenance. While chapters 6 and 7 have demonstrated these techniques, there is a need for further research in different indoor learning environment evaluations using BIM methodologies. Effective collaboration among professionals in the built environment sector in Nigeria is crucial. The Architects Registration Council of Nigeria (ARCON) and allied professional bodies such as the Nigerian Institute of Quantity Surveyors (NIQS), Council of Registered Builders of Nigeria (CORBON), and Council for the Regulation of Engineering in Nigeria (COREN) must work together to promote synergy and foster development in the sector. This collaboration will ensure timely input, improvements, and contributions towards policy implementation and the development of the NNBC and BEE document, in line with their ethical conduct as enshrined in their code of conduct, for the sustainable development of the economy. The Nigerian Institute of Architects (NIA) colloquium program is an annual event that discusses sustainable design and construction issues. Over the years, it has developed into a technical and educational forum for professionals and experts to discuss issues at the global, regional, sub-regional, and national levels relating to the built environment.

- Recommendations to Academics: For academic experts, it is important to create and measure various indices through research, instrumentation, and experimentation. Scholarly articles can establish new standards for policy guides based on the data obtained in Chapters 3 to 7 regarding new comfort temperature. This shows the possibility and significance of developing different forms of indices for the various climatic zones of Nigeria. Conducting a wide range of such studies can provide valuable input for our building code, as requested by the BEE document currently under production.
- Various research constraints limit the assessment of building performance regarding thermal comfort provision, particularly in institutional buildings such as universities. More studies are needed in other areas of thermal comfort, such as visual and noise comfort, to improve building performance and create a sustainable learning environment. The research has focused on the whole thermal comfort building analysis. However, further research is necessary to examine comfort areas related to heat stress, which can impact the health and well-being of occupants in this climate.
- Also, it was highlighted in Chapter 1 that Indoor Environmental Quality (IEQ) research encompasses a broad spectrum of parameters beyond thermal comfort alone. Thus, it is crucial to encourage research in other areas to achieve a sustainable learning environment. For instance, it is essential to research other comfort types or indices, such as visual and noise comfort, to ensure that occupants' well-being is taken care of. Through this research, which analysed the entire building's thermal comfort provision. This will help to ensure the health and well-being of occupants in this climate.

8.3 Summary of Achievement and Design Strategy

- The literature review highlights the significant research gap that needs to be filled in the study.
- The study indicates that the humidity and noise levels were determined within the satisfactory minimum threshold. In contrast, the air temperature and CO_2 level were relatively high compared with the minimum permission comfort level.
- The buildings' retrofitting resulted in the establishment of the minimum effective window shading width, while the incorporated roof shading provides solar protection and serves as solar PV base support.
- Additionally, renewable energy utilisation through PV installation can generate 184 and 212.58MWh of electricity for classroom and studio buildings, respectively.
- The studio and classroom complexes recorded a daylight factor (DLF) of 4.2% and 1.6% and illuminance levels of 563 Lux and 423 Lux, respectively.
- Parametric simulation results in a 28% and 32% cooling load reduction for the classroom and studio complex, respectively.
- The minimum window-to-wall ratio (WWR) was determined to be within 0.24 to 0.30 to avoid overheating.
- A higher standard effective temperature (SET) for learning buildings in Nigeria's hot and dry climate was established, to be within 27.0-32.0°C, with a comfort temperature range of 29.1- 29.5°C.
- This scholarly article will establish new standards for policy guides based on the data obtained regarding new comfort temperatures. These

8.4 Limitations of the Study

The experimental work of this study was restricted to monitoring a limited number of buildings using temperature and humidity measuring instruments to evaluate building occupants' thermal comfort. This is mainly due to time constraints for the monitoring period and limited funding to acquire additional instruments to collect data for more building evaluations in other or same climatic zones and extend the scope of the research to assess for example air movement, lighting, and acoustics in the buildings. The additional data could benefit the accuracy of the IESVE computer model results and correlating architectural design characteristics with comfort indices.

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APPENDIX I

PARTICIPANT INFORMATION SHEET

Participant Information Sheet

Date: 20/8/2021

Title of Study: **Thermal Comfort and Indoor Environmental Quality Survey**

Name of Researcher: Aminu Adamu Bena **Supervisor:** Prof. Mark Gillott

We invite you to participate in our research survey titled Thermal Comfort and Indoor Environmental Quality Survey. Participation in the survey is voluntary and you can withdraw at any point. By participating in the survey, you declare that the information shared is yours and will not hold any identifiable information of another individual or individuals. The data collected in this survey will be anonymous and shall be used for statistical analysis and, eventually, for publication in academic journals and international conferences. The information provided may include editing, duplication, and incorporation in other works such as posters, papers, and conference presentations. The survey information collected will not be used for commercial purposes. However, your participation will remain anonymous and confidential. The overall data will be stored in a secure location in accordance with University of Nottingham regulations, including the General Data Protection Regulation (GDPR) enforced from May 2018.

What is the purpose of the study?

This survey is a part of my PhD study on Thermal Comfort and Indoor Environmental Quality Survey assessment. The study focuses on how environmental factors affect users of the University learning environment in terms of indoor thermal comfort perception, health, and well-being because of the impact of overheating due to solar radiation in Nigeria's hot/dry climate.

Do I have to take part?

You can decide whether to take part. If you decide to take part, you are free to withdraw at any time and without giving a reason. These are your rights.

What will happen to me if I take part?

- Participants will be requested to read and accept by ticking the consent contents in the questionnaire section. This permits the researcher to use the data collected in the study. Participant personal or demographic data, such as name, email, or postal address, will not be collected in this study.
- Participants will be briefed on a specific time and period to start the survey, and WIFI access will be provided.

- Participants are requested to respond to the online questionnaire while in the classroom/learning environment.

<u>The survey structure covers:</u>

The structure of this survey include.

- Assessment and voting of the user perception, thermal comfort, and indoor environmental quality of educational buildings in hot/dry climate of Nigeria.
- Assessment of the effects of overheating on an existing university building in the climatic zone.
- The influence of building form shape on thermal comfort performance and energy efficiency.

Expenses and payments

Participants will not be paid any form of allowance to participate in the study.

What are the possible disadvantages and risks of taking part?

There are no risks, disadvantages, or inconveniences of taking part in the study.

What if there is a problem?

For further information or formal enquiry regarding any problem experience, e-mail the research team or contact the faculty research ethics officer. They will provide immediate solutions. All contact details are given at the end of this information sheet.

What will happen if I don't want to carry on with the study?

Your participation is voluntary, and you are free to withdraw at any time without giving any reason; it is your legal right.

Who is organising and funding the research?

The BEE research team organises this research in the Department of Architecture and Built Environment, University of Nottingham. It has been funded by the Petroleum Technology Development Fund (PTDF) Scholarship, Nigeria.

Who has reviewed the study?

This study has been reviewed and approved by the ethics committee at university levels and faculty levels, the Faculty of Engineering Research Ethics Committee. All research in the University of Nottingham is managed and administered by the Research and Ethics Committee, The University of Nottingham and the Faculty of Engineering have an ethics procedure that requires all staff and students to apply for ethical approval before conducting any research study involving human participants. Collecting data about individuals requires adherence to the University and Faculties Code of Research Conduct and Research Ethics.

Further information and contact details: Researcher: Aminu Adamu Bena, ezxaa26@exmail.nottingham.ac.uk

Supervisor/PI: Prof. Mark Gillott, lazmcg@exmail.nottingham.ac.uk Faculty Ethics Administrator: Donna Astill-Shipman. pazdma@exmail.nottingham.ac.uk

APPENDIX II

University of Nottingham
UK | CHINA | MALAYSIA

Survey Invitation Details

We invite you to participate in our research survey titled Thermal Comfort and Indoor Environmental Quality Survey. The survey is part of the PhD research study that focused on how environmental factors affect users of the University learning environment in terms of indoor thermal comfort perception, health, and well-being because of the impact of overheating due to solar radiation in Nigeria's hot/dry climatic zone.

The participants will not be asked about their personal data (names, e-mails, and addresses. All academic staff and students of the faculty of Environmental Science, Federal University Birnin Kebbi, are eligible to participate. I will be grateful if you can participate via the link provided below.

The survey will take around 15 minutes to complete.

- Participants will be briefed on the specific time and period of the survey, and WIFI access will be provided.
- Participants are requested to respond to the online questionnaire in the Studios/classrooms learning environments.

This study has been reviewed and approved by the Faculty of Engineering Ethics Committee of the University of Nottingham, UK.

It can be accessed on.

https://docs.google.com/forms/d/1fPa1oAOzOa8dNRfxw1oFfbZM2_4XPCLLtzeKKXgIQAs/edit

Thank you.

Aminu Adamu Bena

PhD Research Student

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APPENDIX IIIA and IVA (QUESTIONNAIRE MODEL)

A. THERMAL COMFORT & INDOOR ENVIRONMENTAL QUALITY SURVEY

Thank you very much for for your participation.

Participant information:

This survey is part of my PhD study on thermal comfort and indoor environmental quality survey. The study focuses on assessment of university learning environment in terms of user thermal comfort perception, energy efficiency, indoor environment quality and health and well being.

The questionnaire will take 15 minutes to fill, and the structure of this survey include:

- User perception votes of the indoor environment in hot/dry climate of Nigeria
- Assessment of the effects of overheating in an existing university building in the climatic zone.
- The influence of building form shape on thermal comfort performance and energy efficiency.

* Required

INFORMED CONSENT

Please take time to read the following information carefully.

1. Participation in the survey is entirely voluntary, and you can decide to withdraw at any time during the survey. *

   Mark only one oval.

   ⬭ I agree

2. The data collected in this online survey is anonymous, will only be used for academic publication in conferences and journals, and for statistical analysis. Information you provided will form part of the PhD research work and may be edited, duplicated, incorporated, or use in other works such as poster, paper, and website presentation, and will not be used for commercial purposes. The data collected will be stored in a secured location in accordance with the University of Nottingham privacy notice and guidelines on General Data Protection Regulation (GDPR). (https://www.nottingham.ac.uk/utilities/privacy/privacy:information-for-students-and-applicants.aspx). *

   Mark only one oval.

   ⬭ I agree

B. Declaration

3. I declare that the information provided is solely mine and not the views of other individuals. *

   Mark only one oval.

   ⬭ I agree

C. Personal survey questions

4. GENDER *

   Mark only one oval.

   ⬭ Male
   ⬭ Female

5. AGE *

Mark only one oval.

- 18-27
- 28-37
- 38-47
- 48-57
- 58-67

6. RESPONDENT EDUCATIONAL LEVEL

Mark only one oval.

- Preliminary/basic level
- 100 level (undergraduate)
- 200 level (undergraduate)
- 300 level (undergraduate)
- 400 level (undergraduate)
- 500 level (undergraduate)
- Postgraduate level
- Other: ____________

7. IDENTITY *

Mark only one oval.

- Student
- Lecturer
- Administrative staff
- Other: ____________

8. BUILDING NAME *

9. DATE *

Example: January 7, 2019

10. TIME OF SURVEY *

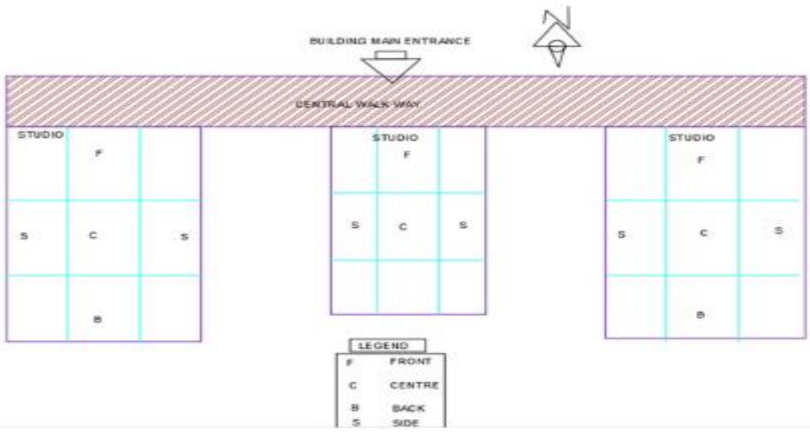
Example: 8:30 AM

11. FLOOR LEVELS *

Mark only one oval.

- Ground
- 1st Floor

Use the Studios floor plan to indicate your sitting position below.



12. Check your sitting position *

Mark only one oval per row.

	Left	Centre	Right
Row 1	⬭	⬭	⬭
Row 2	⬭	⬭	⬭
Row 3	⬭	⬭	⬭

13. Indicate the items of clothing you are currently wearing. (Check all that apply). *

Check all that apply.

- [ ] Short sleeve shirt/Skirt
- [ ] Long sleeve shirt/Skirt
- [ ] Trousers/Shirt
- [ ] Short top/Short skirt
- [ ] Jumper/Trousers
- [ ] Male Trad. Attire
- [ ] Jacket
- [ ] Track suite
- [ ] Coat/Trouser &Tie
- [ ] Tights top/bottom
- [ ] Short socks
- [ ] Slippers
- [ ] Sandals
- [ ] Cover Shoes
- [ ] Boots
- [ ] Female Trad. Attire

Other: [ ] ____________________

E. Thermal comfort parameters

Please, score the following questions according to your subjective feeling; the score is divided into seven levels: (-3 = Cold, -2 = Cool, -1 = Slightly Cool, 0 = Neutral, + 1 = Slightly Warm, + 2 = Warm + 3 = Hot.). Check the option that apply.

14. 1. How would you consider the thermal sensation in the hot season? *

Mark only one oval.

- ⬭ -3. Cold
- ⬭ -2. Cool
- ⬭ -1. Slightly cool
- ⬭ 0. Neutral
- ⬭ +1. Slightly warm
- ⬭ +2. Warm
- ⬭ +3. Hot

15. 2. How would you describe the thermal conditions in winter/rainy season? *

Mark only one oval.

- ⬭ -3. Cold
- ⬭ -2. Cool
- ⬭ -1. Slightly cool
- ⬭ 0. Neutral
- ⬭ +1. Slightly warm
- ⬭ +2. Warm
- ⬭ +3. Hot

16. 3. At this current time what is the feeling of temperature in your space? *

Description: 1. Very uncomfortable, 2. Uncomfortable, 3. Slightly uncomfortable, 4. Neutral, 5. Slightly comfortable, 6. Comfortable, and 7. Very comfortable

Mark only one oval.

	1	2	3	4	5	6	7	
Very uncomfortable	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Very comfortable

17. 4. At this current time what is the feeling of humidity in your space? *

Description: 1. Very uncomfortable, 2. Uncomfortable, 3. Slightly uncomfortable, 4. Neutral, 5. Slightly comfortable, 6. Comfortable, and 7. Very comfortable

Mark only one oval.

	1	2	3	4	5	6	7	
Very uncomfortable	◯	◯	◯	◯	◯	◯	◯	Very comfortable

18. 5. How satisfied are you with the level of fresh air in your space? *

Description: 1. Very dissatisfied, 2. Dissatisfied, 3. Slightly dissatisfied, 4. Neutral, 5. Slightly satisfied, 6. Satisfied, and 7. Very satisfied

Mark only one oval.

	1	2	3	4	5	6	7	
Very dissatisfied	◯	◯	◯	◯	◯	◯	◯	Very satisfied

19. 6. How comfortable are you with day lighting in the lecture room workspace? *

1. Very uncomfortable, 2. Uncomfortable, 3. Slightly uncomfortable, 4. Neutral, 5. Slightly comfortable, 6. Comfortable, and 7. Very comfortable

Mark only one oval.

	1	2	3	4	5	6	7	
Very uncomfortable	◯	◯	◯	◯	◯	◯	◯	Very comfortable

20. 7. How satisfied are you with the noise level in the indoor space? *

Description: 1. Very dissatisfied, 2. Dissatisfied, 3. Slightly dissatisfied, 4. Neutral, 5. Slightly satisfied, 6. Satisfied, and 7. Very satisfied

Mark only one oval.

	1	2	3	4	5	6	7	
Very dissatisfied	◯	◯	◯	◯	◯	◯	◯	Very satisfied

21. 8. When is the environmental thermal comfort most often a problem? (check all that apply): *

Check all that apply.

- [ ] Morning (before 11am)
- [ ] Mid-day (11am-2pm)
- [ ] Afternoon (2pm-5pm)
- [ ] Evening (After 5pm)
- [ ] Night time
- [ ] Weekends/holidays

Other: [ ] ____________________

22. 9. How would you best describe the source of this discomfort? (Check all that apply): *

Check all that apply.

- [ ] Humidity too low (dry)
- [ ] Humidity too high
- [ ] Air movement too low
- [ ] Air movement too high
- [ ] Heat from incoming Sun
- [ ] Heat from office equipment
- [ ] Dust from external environment
- [ ] My area is hotter than other areas
- [ ] Hot surrounding surfaces
- [ ] Poor air quality
- [ ] Insufficient openings for ventilation
- [ ] Cooling system does not respond quickly
- [ ] Poor clothing policy

Other: [ ] ____________________

23. 10. Do you experience any of the following symptoms when working in this environment? (check all that apply). *

Check all that apply.

- [ ] Fatigue
- [ ] Sweating
- [ ] Headache
- [ ] Dizziness
- [ ] Sleepy
- [ ] Restlessness

Other: [ ] ____________________

F. Control and activities.

24. 11. Which of the following do you personally adjust or control in your space? (Check all that apply). *

Check all that apply.

- [ ] Doors
- [ ] Windows
- [ ] Blinds/curtains
- [ ] Light
- [ ] Air conditioning units
- [ ] Fans
- [ ] External Windows shading

Other: [ ] ____________________

25. 12. Do you use any of the items listed in question 11 to improve thermal conditions of your building often? *

Mark only one oval.

- ( ) Yes
- ( ) No

26. 13. In general, how often do you use any of the controls provided in the building for thermal regulation? *

Description: 1. Never, 2. Rarely, 3. Occasionally, 4. Neutral, 5. Slightly regularly, 6. Regularly and 7. Very regularly.

Mark only one oval.

	1	2	3	4	5	6	7	
Never	( )	( )	( )	( )	( )	( )	( )	Regularly

27. 14. How does the thermal comfort in your indoor space interferes / enhanced with your ability to carry out activities? *

Description: 1. Greatly interfere, 2. interferes, 3. Slightly interfere, 4. Neutral, 5. Slightly enhanced, 6. Enhanced and 7. Greatly enhanced

Mark only one oval.

	1	2	3	4	5	6	7	
Greatlt interferes	( )	( )	( )	( )	( )	( )	( )	Greatly enhances

28. 15. How comfortable are you with artificial lighting in the lecture room workspace? *

Descriptio: 1. Very uncomfortable, 2. Uncomfortable, 3. Slightly uncomfortable, 4. Neutral, 5. Slightly comfortable, 6. Comfortable, and 7. Very comfortable

Mark only one oval.

	1	2	3	4	5	6	7	
Very uncomfortable	( )	( )	( )	( )	( )	( )	( )	Very comfortable

29. 16. How satisfied are you with this level of control? *
Description: 1. Very dissatisfied, 2. Dissatisfied, 3. Slightly dissatisfied, 4. Neutral, 5. Slightly satisfied, 6. Satisfied, and 7. Very satisfied

Mark only one oval.

	1	2	3	4	5	6	7	
Very dissatisfied	◯	◯	◯	◯	◯	◯	◯	Very satisfied

30. 17. What is your activity level right now? (check all that apply). *

Check all that apply.

- [ ] Reading
- [ ] Writing
- [ ] Standing
- [ ] Seating
- [ ] Light activity
- [ ] Medium activity
- [ ] High activity

Other: [ ] ____________________

31. 18. What is your perception of the indoor air quality?(check all that apply). *

Check all that apply.

- [ ] Fresh
- [ ] Odourless
- [ ] Smelly
- [ ] Comfortable
- [ ] A little polluted
- [ ] Polluted
- [ ] Muffled
- [ ] Still

Other: [ ] ____________________

G. Building appreciation

32. 19 Score your level of satisfaction with the buildings form, shape and aesthetic. *
Description: 1. Very dissatisfied, 2. Dissatisfied, 3. Slightly dissatisfied, 4. Neutral, 5. Slightly satisfied, 6. Satisfied, and 7. Very satisfied

Mark only one oval.

	1	2	3	4	5	6	7	
Very dissatisfied	◯	◯	◯	◯	◯	◯	◯	Very satisfied

33. 20. What is it that you like or dislike about the building form, shape and structure? *

34. 21. What do you like or dislike about the interior's spaces, elements of the building and the aesthetics? *

Thank you for your participation!
For further information please contact the research team.
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Supervisor: Prof. Mark Gillott: mark.gillott@nottingham.ac.uk
Department of Architecture and Built Environment, Faculty of Engineering, University of Nottingham, UK.

APPENDIX IIIB (Arch. Studio Questionnaire Results; Tables)

ARCH STUDIO COMPLEX, FES-FUBK

QUESTIONNAIRE CHARTS AND TABLES

GENERAL QUESTIONS

A. Timestamp; 2021/09/06 9:34:43 AM GMT to 2021/09/07 5:55:47 PM GMT
B. Timestamp; 2021/09/08 11:13:08 AM GMT to 2021/09/08 11:32:12 AM GMT
C. Timestamp; 2021/09/09 12:08:45 PM GMT to 2021/09/09 12:33:37 PM GMT
D. Timestamp; 2021/09/13 11:37:30 AM GMT to 2021/09/13 12:09:23 PM GMT

1. Participation in the survey is entirely voluntary, and you can decide to withdraw at any time during the survey.

I Agree

The data collected in this online survey is anonymous, in line with the Nottingham privacy notice and guidelines on General Data Protection Regulation (GDPR). (https://www.nottingham.ac.uk/utilities/privacy/privacy:information-for-students-and-applicants.aspx).

I Agree.

2. I declare that the information provided is solely mine and not the views of other individuals.

I Agree

3. GENDER

	Gender	Count	% Count
1	Female	8	13
2	Male	54	87
		62	100

4. AGE

	Age Group	Count	% Count
1	18-27	40	65
2	28-37	11	18
3	38-47	7	11
4	48-57	1	2
5	58-67	3	5
		62	100

5. RESPONDENT'S EDUCATIONAL LEVEL

	Level	Count	% Count
1	100 Level	13	21
2	200 Level	5	8
3	300 Level	6	10
4	400 Level	25	40
5	Lecturers	13	21
		62	**100**

6. IDENTITY

	Identity	Count	% Count
1	Lecturer	13	21
2	Students	49	79
		62	**100**

7. BUILDING NAME; ARCHITECTURAL STUDIO COMPLEX
8. DATE; 17/05/2020
9. TIME OF SURVEY; 09:00AM to 15:00PM
10. FLOOR LEVELS

	Building levels	Count	% Count
1	First Floor	31	50
2	Ground Floor	31	50
		62	**100**

11. Check your sitting position.

	Sitting Position	Counts	% Count
1	Left	17	27
2	Centre	26	42
3	Right	19	31
		62	**100**

12. Indicate the items of clothing you are currently wearing. (Check all that apply).

	Categories of Clothing Wear	Votes Count	% Votes
1	Female Traditional Attire with shoes	6	10
2	Male Traditional Attire with shoes	26	42
3	Short sleeve Shirt and Skirts/shoes	1	2
4	Short sleeve Shirt and Trousers/shoes	13	21
5	Long sleeve shirts and skirts/shoes	3	5
6	Long sleeve Shirt and Trousers/shoes	6	10
7	Tracksuit sports	7	11
		62	**100**

"Q1T. How would you consider the thermal sensation in the hot season?"

	T Sensation scale	TSVote	PSVote
1	-3 cold	0	0
2	-2 cool	1	2
3	-1 slightly cool	1	2
4	0- Neutral	0	0
5	+1 Slightly Warm	5	8
6	+2 Warm	12	19
7	+3 Hot	43	69
		62	**100**

"Q2T. How would you describe the thermal conditions in winter/rainy season?"

	T Sensation scale	TSVote	PSVote
1	-3 cold	5	8
2	-2 cool	12	19
3	-1 slightly cool	12	19
4	0-Neutral	9	15
5	+1 Slightly Warm	6	10
6	+2 Warm	13	21
7	+3 Hot	5	8
		62	**100**

"Q3T. At this current time, what is the feeling of temperature in your space?"

	Comfort Scale	Votes	% Votes
1	-3 Very uncomfortable	9	15
2	-2 Uncomfortable	16	26
3	-1 Slightly uncomfortable	12	19
4	0- Neutral	9	15
5	+1 Slightly comfortable	10	16
6	+2 Comfortable	1	2
7	+3 Very Comfortable	5	8
		62	**100**

"Q4T. At this current time, what is the feeling of humidity in your space?"

	Comfort Scale	CSV	PSV
1	-3 Very uncomfortable	6	10
2	-2 Uncomfortable	12	19
3	-1 Slightly uncomfortable	11	18
4	0- Neutral	15	24
5	+1 Slightly comfortable	8	13
6	+2 Comfortable	6	10
7	+3 Very Comfortable	4	6
		62	100

"Q5T. How satisfied are you with the level of fresh air in your space? "

	Satisfaction Scale	CSV	% Comfort Vote
1	-3 Very dissatisfied	5	8
2	-2 Dissatisfied	15	24
3	-1 Slightly dissatisfied	16	26
4	0-Neutral	11	18
5	+1 Slightly satisfied	8	13
6	+2 Satisfied	4	6
7	+3 Very Satisfied	3	5
		62	100

"Q6T. How comfortable are you with daylighting in the lecture room workspace?"

	Comfort Scale	CSV	% CS Vote
1	-3 Very uncomfortable	1	2
2	-2 Uncomfortable	3	5
3	-1 Slightly uncomfortable	8	13
4	0-Neutral	5	8
5	+1 Slightly comfortable	10	16
6	+2 Comfortable	15	24
7	+3 Very comfortable	20	32
		62	100

"Q7T. How satisfied are you with the noise level in the indoor space?"

	Satisfaction Scale	Satisfaction Vote	% Sat. Vote
1	-3 Very dissatisfied	3	2
2	-2 Dissatisfied	9	7
3	-1 Slightly dissatisfied	22	18
4	0-Neutral	31	26
5	+1 Slightly satisfied	33	27
6	+2 Satisfied	15	12
7	+3 Very satisfied	8	7
		121	**100**

"Q8T. When is environmental thermal comfort most often a problem? (Check all that apply):

	Time and Period	Frequency	% Vote
1	Morning (before 11 am)	4	2
2	Mid-day (11 am-2 pm)	98	46
3	Afternoon (2pm-5pm)	100	47
4	Evening (After 5 pm)	10	5
5	Night-time	2	1
		214	**100**

Q9T. How would you best describe the source of this discomfort? (Check all that apply):

	Sources of Discomfort	Frequency	% Votes
1	Air movement too high	3	1
2	Air movement too low	64	20
3	Cooling does not respond Quickly	2	1
4	Dust from the External Environment	9	3
5	Heat from incoming Sun	103	33
6	Heat from office equipment	2	1
7	Hot surrounding surfaces	8	3
8	Humidity too high	3	1
9	Humidity too low (dry)	86	27
10	My area is hotter than other areas	10	3
11	Poor Air Quality	20	6
12	Poor clothing policy	4	1
		314	**100**

Q10T. Do you experience any of the following symptoms when working in this environment? (Check all that apply).

	Sickness and Symptoms	Frequency	% Votes
1	Fatigue	52	18
2	Restlessness	27	9
3	Sweating	108	37
4	Headache	42	15
5	Dizziness	19	7
6	Tiredness	6	2
7	Sleepy	35	12
		289	**100**

"Q11T. Which of the following do you personally adjust or control in your space? (Check all that apply)."

	Adjustment/control	Frequency	% Vote
1	Air conditioning units	70	17
2	Fans	116	29
3	Blinds/Curtains	0	0
4	Doors	42	10
5	Windows	101	25
6	External Win, Shading	0	0
7	Light	76	19
		405	**100**

"Q12T. Do you use any of the items listed in question 11 to improve thermal conditions of your building often?"

	Do you use Items in Q11	Votes Count	% Votes
1	No	9	7
2	Yes	112	93
		121	**100**

Q13T. In general, how often do you use any of the controls provided in the building for thermal regulation?

	Scale	Votes Count	% Votes
1	Never	1	1
2	Rarely	0	0
3	occasionally	0	0
4	Neutral	0	0
5	Slightly	9	7
6	Regularly	34	28
7	Very regularly	77	64
		121	**100**

"Q14T. How does the thermal comfort in your indoor space enhance/interfere with your ability to carry out activities?"

	Scale	Vote count	% Vote
1	Greatly interfere	1	1
2	Interfere	3	2
3	Slightly interfere	5	4
4	Neutral	10	8
5	Slightly enhanced	26	21
6	Enhanced	53	44
7	Greatly enhanced	23	19
		121	**100**

"Q15T. How comfortable are you with artificial lighting in the lecture room workspace?"

	Comfort Scale	Comfort vote	% Comfort vote
1	-3 Very uncomfortable	0	0
2	-2 Uncomfortable	3	2
3	-1 Slightly uncomfortable	0	0
4	0-Neutral	14	12
5	+1 Slightly comfortable	35	29
6	+2 Comfortable	50	41
7	+3 Very comfortable	19	16
		121	**100**

"Q16T. How satisfied are you with this level of control?"

	Satisfaction Scale	Satisfaction Vote	% Satisfaction vote
1	-3 Very dissatisfied	0	0
2	-2 Dissatisfied	5	4
3	-1 Slightly dissatisfied	7	6
4	0-Neutral	10	8
5	+1 Slightly satisfied	30	25
6	+2 Satisfied	46	38
7	+3 Very satisfied	23	19
		121	**100**

"Q17T. What is your activity level right now? (Check all that apply)."

	Activity Levels	Votes Count	% votes
1	Light activity	34	14
2	Medium activity	41	17
3	High activity	11	5
4	Reading	33	14
5	Seating	94	40
6	Standing	5	2
7	Writing	17	7
		235	**100**

"Q18T. What is your perception of indoor air quality? (Check all that apply)."

	Air quality	Vote count	% Vote
1	A little polluted	44	27
2	Comfortable	36	22
3	Fresh	23	14
4	Muffled	21	13
5	odourless	17	11
6	Still	12	7
7	Polluted	8	5
		161	**100**

Q19T. Score your level of satisfaction with the building's form, shape, and aesthetic.

	Satisfaction Scale	Satisfaction vote	% Satisfaction vote
1	-3 Very dissatisfied	0	0
2	-2 Dissatisfied	0	0
3	-1 Slightly dissatisfied	0	0
4	0-Neutral	4	3
5	+1 Slightly satisfied	10	8
6	+2 Satisfied	65	54
7	+3 Very satisfied	42	35
		121	**100**

"Q20T. What do you like or dislike about the external features of building form, shape, and structure?".

	Building Form (external features)	Like vote count	Dislike vote count	Total	% Like	% Dislike
1	Form Character (Shape/H)	74	5	79	47	19
2	Form /Element Placement	42	6	48	27	23
3	Passive Features of Building Form	40	15	55	26	58
		156	**26**	**182**	**100**	**100**

Q21T. What do you like or dislike about the interior spaces of the building and the aesthetics?

	Interior Space Planning	Like vote	Dislike vote	Total	% Like	% Dislike
1	Indoors-space configuration	44	10	54	40	26
2	Placement of elements	17	18	35	15	46
3	Aesthetics features	49	11	60	45	28
		110	**39**	**149**	**100**	**100**

APPENDIX IVB (Classroom Questionnaire Results; Tables)

CH4-CLASSROOM COMPLEX, FES-FUBK

QUESTIONNAIRE CHARTS AND TABLES

GENERAL QUESTIONS

E. Timestamp; 2021/09/06 9:34:43 AM GMT to 2021/09/07 5:55:47 PM GMT
F. Timestamp; 2021/09/08 11:13:08 AM GMT to 2021/09/08 11:32:12 AM GMT
G. Timestamp; 2021/09/09 12:08:45 PM GMT to 2021/09/09 12:33:37 PM GMT
H. Timestamp; 2021/09/13 11:37:30 AM GMT to 2021/09/13 12:09:23 PM GMT

13. Participation in the survey is entirely voluntary, and you can decide to withdraw at any time during the survey.

I Agree

The data collected in this online survey is anonymous, in line with Nottingham's privacy notice and guidelines on the General Data Protection Regulation (GDPR). (https://www.nottingham.ac.uk/utilities/privacy/privacy:information-for-students-and-applicants.aspx). I Agree.

14. I declare that the information provided is solely mine and not the views of other individuals. I Agree
15. GENDER

Table 4-Q1. Gender of the Respondents

S/no,	Gender	Count	% Count
1	Female	31	26
2	Male	90	74
		121	**100**

16. AGE

Table 4-Q2. Age of the Respondents

S/no.	Age Group	Count	% Count
1	18-27	96	79
2	28-37	18	15
3	38-47	7	6
4	48-57	0	0
5	58-67	0	0
		121	**100**

17. RESPONDENT'S EDUCATIONAL LEVEL

Table 4-Q3. Respondent's education level

S/no.	Level	Count	Percentage
1	100 Level	13	11
2	200 Level	27	22
3	300 Level	26	21
4	400 Level	49	40
5	Lecturers	6	5
		121	**100**

18. IDENTITY

Table 4-Q4. Identity of the respondent

	Identity	Count	% Count
1	Lecturer	6	5
2	Students	115	95
		121	**100**

19. BUILDING NAME; DEPT OF BUILDING CLASSROOM COMPLEX
20. DATE; 27/04/2021
21. TIME OF SURVEY; 09:00AM to 15:00PM
22. FLOOR LEVELS

Table 4-Q5. Building floor levels

S/no.	Building levels	Frequency	Percentage
1	First Floor	54	45
2	Ground Floor	67	55
		121	**100**

Check your sitting position

Table 4-Q6. Respondent's sitting position in the building

S/no.	Sitting Position	Frequency	%Votes
1	Left	40	33
2	Centre	41	34
3	Right	40	33
		121	**100**

23. Indicate the items of clothing you are currently wearing. (Check all that apply).

Table 4-Q7. Respondent's categories of clothing wear

S/no	Categories of Clothing Wear	Frequency	% Frequency
1	Female Traditional Attire	19	16
2	Male Traditional Attire	28	23
3	Short sleeve Shirt and Skirts	11	9
4	Short sleeve Shirt and Trousers	44	36
5	Long sleeve shirts skirt	5	4
6	Long sleeve Shirt and Trousers	10	8
7	Tracksuit sports	4	3
		121	**100**

Q1T. How would you consider the thermal sensation in the hot season?

Table 4-Q8. Thermal sensation votes of the hot season

S/no	Thermal Sensation scale	Vote count	%Vote
1	-3 cold	0	0
2	-2 cool	2	2
3	-1 slightly cool	0	0
4	0- Neutral	3	2
5	+1 Slightly Warm	2	2
6	+2 Warm	4	3
7	+3 Hot	110	91
		121	**100**

Q2T. How would you describe the thermal conditions in the winter/rainy season?

Table 4-Q9. Thermal sensation in the winter/rainy season

S/no.	Thermal Sensation scale	Votes count	% Votes
1	-3 cold	18	15
2	-2 cool	65	54
3	-1 slightly cool	20	17
4	0- Neutral	13	11
5	+1 Slightly Warm	2	2
6	+2 Warm	0	0
7	+3 Hot	3	2
		121	**100**

Q3T. At this current time, what is the feeling of temperature in your space?

Table 4-Q10.The sensation of temperature in a space

	Comfort Scale	(F)Votes	% Votes
1	-3Very uncomfortable	31	26
2	-2 Uncomfortable	41	34
3	-1Slightly uncomfortable	18	15
4	0- Neutral	6	5
5	+1Slightly comfortable	13	11
6	+2 Comfortable	9	7
7	+3Very Comfortable	3	2
		121	**100**

Q4T. At this current time, what is the feeling of humidity in your space?

Table 4-Q11.The sensation of humidity in space

S/no.	Comfort Scale	Votes count	% Vote
1	-3Very uncomfortable	19	16
2	-2 Uncomfortable	42	35
3	-1Slightly uncomfortable	32	26
4	0- Neutral	7	6
5	+1Slightly comfortable	13	11
6	+2 Comfortable	8	7
7	+3Very Comfortable	0	0
		121	**100**

Q5T. How satisfied are you with the level of fresh air in your space?

Table 4-Q12.Thermal satisfaction with the supply of fresh air in space

S/no.	Satisfaction Scale	Votes count	% Votes
1	Very dissatisfied	53	44
2	Dissatisfied	23	19
3	Slightly dissatisfied	12	10
4	Neutral	10	8
5	Slightly satisfied	11	9
6	Satisfied	8	7
7	Very satisfied	4	3
		121	**100**

Q6T. How comfortable are you with daylighting in the lecture room/workspace?

Table 4.Q13. Comfortable with daylighting in the lecture room/workspace

S/no.	Comfort Scale	Votes count	% Vote
1	Very uncomfortable	5	4
2	Uncomfortable	17	14
3	Slightly uncomfortable	11	9
4	Neutral	16	13
5	Slightly comfortable	31	26
6	Comfortable	20	17
7	Very comfortable	21	17
		121	**100**

Q7T. How satisfied are you with the noise level in the indoor space?

Table 4.Q14. Satisfaction with the Noise level in the indoor environment

S/no.	Satisfaction Scale	Votes count	% Vote
1	Very dissatisfied	3	2
2	Dissatisfied	9	7
3	Slightly dissatisfied	22	18
4	Neutral	31	26
5	Slightly satisfied	33	27
6	Satisfied	15	12
7	Very satisfied	8	7
		121	**100**

Q8T. When is environmental thermal comfort most often a problem? (Check all that apply).

Table 4.Q15. Period of experiencing thermal discomfort

S/no.	Time and Period	Frequency	% Vote
1	Morning (before 11am)	11 am	2
2	Mid-day (11 am-2 pm)	98	46
3	Afternoon (2 pm-5 pm)	100	47
4	Evening (After 5 pm)	10	5
5	Night-time	2	1
		214	**100**

Q9T. How would you best describe the source of this discomfort? (Check all that apply)

Table 4.Q16. Sources of thermal discomfort

S/no.	Sources of Discomfort	Frequency	% Votes
1	Air movement too high	3	1
2	Air movement too low	64	20
3	Cooling does not respond Quickly	2	1
4	Dust from external Environment	9	3
5	Heat from incoming Sun	103	33
6	Heat from office equipment	2	1
7	Hot surrounding surfaces	48	3
8	Humidity too high	3	1
9	Humidity too low (dry)	86	27
10	My area is hotter than other areas	10	3
11	Poor Air Quality	20	6
12	Poor clothing policy	4	1
		354	**100**

Q10T. Do you experience any of the following symptoms when working in this environment? (Check all that apply).

Table 4.Q17. Types of sickness/ symptoms experienced while working

S/no.	Sickness and Symptoms	Frequency	% Votes
1	Fatigue	52	18
2	Restlessness	27	9
3	Sweating	108	37
4	Headache	42	15
5	Dizziness	19	7
6	Tiredness	6	2
7	Sleepy	35	12
		289	**100**

Q11T. Which of the following do you personally adjust or control in your space? (Check all that apply).

Table 4.Q18. The personal level of equipment adjustment and control

	Adjustment/control	Frequency	% Vote
1	Air conditioning units	70	17
2	Fans	116	29
3	Blinds/Curtains	0	0
4	Doors	42	10
5	Windows	101	25
6	External Win, Shading	0	0
7	Light	76	19
		405	**100**

Q12T. Do you often use any of the items listed in question 11 to improve the thermal conditions of your building?

Table 4.Q19. Indication on the use of thermal control equipment.

	Do you use Items in Q11?	Votes Count	% Votes
1	No	9	7
2	Yes	112	93
		121	**100**

Q13T. In general, how often do you use any of the controls provided in the building for thermal regulation?

Table 4.Q20. The scale of thermal regulation using devices and control

S/no.	Scale	Votes Count	% Votes
1	Never	1	1
2	Rarely	0	0
3	occasionally	0	0
4	Neutral	0	0
5	Slightly	9	7
6	Regularly	34	28
7	Very regularly	77	64
		121	**100**

Q14T. How does the thermal comfort in your indoor space enhance/interfere with your ability to carry out activities?

Table 4.Q21. The level of interference and enhancement on occupant's productivity.

	Scale	Vote count	% Vote
1	Greatly interfere	1	1
2	Interfere	3	2
3	Slightly interfere	5	4
4	Neutral	10	8
5	Slightly enhanced	26	21
6	Enhanced	53	44
7	Greatly enhanced	23	19
		121	**100**

Q15T. How comfortable are you with artificial lighting in the lecture room workspace?

Table 4.Q22. Artificial and Natural lighting comfort in the lecture room

S/no.	Comfort Scale	Votes count	% Comfort vote
1	Very uncomfortable	0	0
2	Uncomfortable	3	2
3	Slightly uncomfortable	0	0
4	Neutral	14	12
5	Slightly comfortable	35	29
6	Comfortable	50	41
7	Very comfortable	19	16
		121	**100**

Q16T. How satisfied are you with the level of control?

Table 4.Q23. Satisfaction with the level of control

S/no.	Satisfaction Scale	Vote count	% Vote
1	Very dissatisfied	0	0
2	Dissatisfied	5	4
3	Slightly dissatisfied	7	6
4	Neutral	10	8
5	Slightly satisfied	30	25
6	Satisfied	46	38
7	Very satisfied	23	19
		121	**100**

Q17T. What is your activity level right now? (Check all that apply).

Table 4.Q24. Respondents' present activity level

S/no.	Activity Levels	Votes Count	% Votes
1	Light activity	34	14
2	Medium activity	41	17
3	High activity	11	5
4	Reading	33	14
5	Seating	94	40
6	Standing	5	2
7	Writing	17	7
		235	**100**

Q18T. What is your perception of indoor air quality? (Check all that apply).

Table 4.Q25. Respondent's perception of indoor air quality

	Air quality	Vote count	% Vote
1	A little polluted	44	27
2	Comfortable	36	22
3	Fresh	23	14
4	Muffled	21	13
5	Odorless	17	11
6	Still	12	7
7	Polluted	8	5
		161	**100**

Q19T. Score your level of satisfaction with the building's form, shape, and aesthetic.

Table 4.Q26. Respondents' satisfaction with the built form.

	Satisfaction Scale	Votes count	% Vote
1	Very dissatisfied	0	0
2	Dissatisfied	0	0
3	Slightly dissatisfied	0	0
4	Neutral	4	3
5	Slightly satisfied	10	8
6	Satisfied	65	54
7	Very satisfied	42	35
		121	**100**

Q20T. What do you like or dislike about the external features of the building's form, shape, and structure?

Table 4.Q27. Respondents' like and dislike appeal of the built-form external features

S/no.	Building Form (external features)	Like vote count	Dislike vote count	Total	% Like	% Dislike
1	Form Character (Shape/H)	74	5	79	47	19
2	Form /Element Placement	42	6	48	27	23
3	Passive Features of Bldg. Element	40	15	55	26	58
		156	**26**	**182**	**100**	**100**

Q21T. What do you like or dislike about the interior spaces of the building and the aesthetics?

Table 4.Q28. Respondents' like and dislike appeal of the built-form interior spaces

	Interior Space Planning	Like vote	Dislike vote	Total	% Like	% Dislike
1	Indoors-space configuration	44	10	54	40	26
2	Placement of elements	17	18	35	15	46
3	Aesthetics features	49	11	60	45	28
		110	**39**	**149**	**100**	**100**

APPENDIX V (Questionnaire SPSS analysis; Tables)

First Research Question
Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
How would you consider the thermal sensation in the hot season? - How would you describe the thermal conditions in winter/rainy season?	Negative Ranks	1	26.00	26.00
	Positive Ranks	53	27.53	1459.00
	Ties	8		
	Total	62		

Z	-6.200
p-vale	.000

Second Research Question:

Kustal Wallis Test

Ranks

	How would you consider the thermal sensation in the hot season?	N	Mean Rank
At this current time what is the feeling of temperature in your space?	Slightly warm	5	41.20
	Warm	12	38.67
	Hot	43	26.98
	Total	60	
At this current time what is the feeling of humidity in your space?	Slightly warm	5	35.20
	Warm	12	37.71
	Hot	43	27.94
	Total	60	
How satisfied are you with the level of fresh air in your space?	Slightly warm	5	41.00
	Warm	12	35.83
	Hot	43	27.79
	Total	60	
How comfortable are you with day lighting in the lecture room workspace?	Slightly warm	5	32.00
	Warm	12	33.83
	Hot	43	29.40
	Total	60	
How satisfied are you with the noise level in the indoor space?	Slightly warm	5	31.70
	Warm	12	26.71
	Hot	43	31.42
	Total	60	

Test Statistics

	At this current time what is the feeling of temperature in your space?	At this current time what is the feeling of humidity in your space?	How satisfied are you with the level of fresh air in your space?	How comfortable are you with day lighting in the lecture room workspace?	How satisfied are you with the noise level in the indoor space?
Kruskal-Wallis H	6.487	3.430	4.122	.684	.741
df	2	2	2	2	2
p-value	.039	.180	.127	.710	.690

Kruskal-Wallis Test

Ranks

	How would you describe the thermal conditions in winter/rainy season?	N	Mean Rank
At this current time what is the feeling of temperature in your space?	Slightly warm	6	12.67
	Warm	13	11.62
	Hot	5	14.60
	Total	24	
At this current time what is the feeling of humidity in your space?	Slightly warm	6	14.50
	Warm	13	9.00
	Hot	5	19.20
	Total	24	
How satisfied are you with the level of fresh air in your space?	Slightly warm	6	13.75
	Warm	13	10.69
	Hot	5	15.70
	Total	24	
How comfortable are you with day lighting in the lecture room workspace?	Slightly warm	6	15.58
	Warm	13	11.73
	Hot	5	10.80
	Total	24	
How satisfied are you with the noise level in the indoor space?	Slightly warm	6	15.17
	Warm	13	10.85
	Hot	5	13.60
	Total	24	

Test Statistics

	At this current time what is the feeling of temperature in your space?	At this current time what is the feeling of humidity in your space?	How satisfied are you with the level of fresh air in your space?	How comfortable are you with day lighting in the lecture room workspace?	How satisfied are you with the noise level in the indoor space?
Kruskal-Wallis H	.674	8.482	2.207	1.652	1.746
df	2	2	2	2	2
Asymp. Sig.	.714	.014	.332	.438	.418

Third Research Question:

Kruskal-Wallis Test

Ranks

	Floor Level	N	Mean Rank
Check your sitting position [Front row]	Ground	11	12.59
	1st Floor	17	15.74
	Total	28	
Check your sitting position [Central row]	Ground	19	16.13
	1st Floor	13	17.04
	Total	32	
Check your sitting position [Back row]	Ground	6	6.17
	1st Floor	6	6.83
	Total	12	

Test Statistics	Check your sitting position [Front row]	Check your sitting position [Central row]	Check your sitting position [Back row]
Kruskal-Wallis H	1.286	.089	.147
df	1	1	1
Asymp. Sig.	.257	.765	.702

Fourth Research Question:

Kruskal-Wallis Test

Ranks

	How would you consider the thermal sensation in the hot season?	N	Mean Rank
When is the environmental thermal comfort most often a problem?Morning before 11am	Slightly warm	5	33.00
	Warm	12	30.50
	Hot	43	30.21
	Total	60	
When is the environmental thermal comfort most often a problem?Mid-day 11am-2pm	Slightly warm	5	38.50
	Warm	12	30.50
	Hot	43	29.57
	Total	60	
When is the environmental thermal comfort most often a problem?2pm-5pm	Slightly warm	5	18.50
	Warm	12	38.50
	Hot	43	29.66
	Total	60	
When is the environmental thermal comfort most often a problem?After 5pm	Slightly warm	5	33.00
	Warm	12	33.00
	Hot	43	29.51
	Total	60	
When is the environmental thermal comfort most often a problem? Night time	Slightly warm	5	27.00
	Warm	12	33.00
	Hot	43	30.21
	Total	60	
When is the environmental thermal comfort most often a problem? Weekends/holidays	Slightly warm	5	30.50
	Warm	12	30.50
	Hot	43	30.50
	Total	60	

Test Statistics

	When is the environmental thermal comfort most often a problem? Morning before 11am	When is the environmental thermal comfort most often a problem? Mid-day 11am-2pm	When is the environmental thermal comfort most often a problem?2pm-5pm	When is the environmental thermal comfort most often a problem? After 5pm	When is the environmental thermal comfort most often a problem? Night time	When is the environmental thermal comfort most often a problem? Weekends/holidays
Kruskal-Wallis H	.499	1.756	6.911	2.121	2.001	.000
df	2	2	2	2	2	2
Asymp. Sig.	.779	.416	.032	.346	.368	1.000

APPENDIX V (Questionnaire SPSS analysis; Tables – CLASSROOM)

Q1. First Research Question:

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The median differences between Q1T. How would you consider the thermal sensation in the hot season? and Q2T. How would you describe the thermal conditions in winter/rainy season? equals 0.	Related-Samples Wilcoxon Signed Rank Test	.000	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .050.

Related-Samples Wilcoxon Signed Rank Test Summary

Total N	121
Test Statistic	5.500
Standard Error	361.052
Standardized Test Statistic	-9.544
Asymptotic Sig.(2-sided test)	.000

Q2. Second Research Question

Ranks

	Q1T. How would you consider the thermal sensation in the hot season?	N	Mean Rank
Q3T. At this current time what is the feeling of temperature in your space?	cool	2	98.25
	Neutral	3	106.67
	Slightly Warm	2	16.00
	Warm	4	92.13
	Hot	110	58.76
	Total	121	
Q4T. At this current time what is the feeling of humidity in your space?	cool	2	107.00
	Neutral	3	90.83
	Slightly Warm	2	79.00
	Warm	4	94.63
	Hot	110	57.80
	Total	121	
Q5T. How satisfied are you with the level of fresh air in your space?	cool	2	103.50
	Neutral	3	107.17
	Slightly Warm	2	119.50
	Warm	4	64.25
	Hot	110	57.79
	Total	121	
Q6T. How comfortable are you with daylighting in the lecture room workspace?	cool	2	111.00
	Neutral	3	80.33
	Slightly Warm	2	111.00
	Warm	4	50.00
	Hot	110	59.05
	Total	121	
Q7T. How satisfied are you with the noise level in the indoor space?	cool	2	83.75
	Neutral	3	68.67
	Slightly Warm	2	117.50
	Warm	4	72.00
	Hot	110	58.95
	Total	121	

Test Statistics[a,b]

	Q3T. At this current time, what is the feeling of temperature in your space?	Q4T. At this current time, what is the feeling of humidity in your space?	Q5T. How satisfied are you with the level of fresh air in your space?	Q6T. How comfortable are you with daylighting in the lecture room workspace?	Q7T. How satisfied are you with the noise level in the indoor space?
Kruskal-Wallis H	15.151	11.486	16.167	10.100	7.276
df	4	4	4	4	4
Asymp. Sig.	.004	.022	.003	.039	.122

a. Kruskal Wallis Test

b. Grouping Variable: Q1T. How would you consider the thermal sensation in the hot season?

Test Statistics[a,b]

	Q3T. At this current time what is the feeling of temperature in your space?	Q4T. At this current time what is the feeling of humidity in your space?	Q5T. How satisfied are you with the level of fresh air in your space?	Q6T. How comfortable are you with day lighting in the lecture room workspace?	12. Indicate the items of clothing you are currently wearing. (Check all that apply).	Q7T. How satisfied are you with the noise level in the indoor space?	Q8T.When is the environmental thermal comfort most often a problem?
Kruskal-Wallis H	15.151	11.486	16.167	10.100	1.083	7.276	18.049
df	4	4	4	4	4	4	4
Asymp. Sig.	.004	.022	.003	.039	.897	.122	.001

a. Kruskal Wallis Test

b. Grouping Variable: Q1T. How would you consider the thermal sensation in the hot season?

Q3. Third Research Question

Ranks

	Q2T. How would you describe the thermal conditions in the winter/rainy season?	**N**	**Mean Rank**
Q3T. At this current time, what is the feeling of temperature in your space?	cold	18	74.06
	cool	65	56.52
	slightly cool	20	66.15
	Neutral	13	57.23
	Slightly Warm	2	59.50
	Hot	3	62.67
	Total	121	
Q4T. At this current time, what is the feeling of humidity in your space?	cold	18	65.61
	cool	65	58.52
	slightly cool	20	55.33
	Neutral	13	72.08
	Slightly Warm	2	97.50
	Hot	3	52.50
	Total	121	
Q5T. How satisfied are you with the level of fresh air in your space?	cold	18	68.75
	cool	65	53.71
	slightly cool	20	63.00
	Neutral	13	79.12
	Slightly Warm	2	89.25
	Hot	3	61.83
	Total	121	
Q6T. How comfortable are you with daylighting in the lecture room workspace?	cold	18	77.08
	cool	65	54.25
	slightly cool	20	57.13

	Neutral	13	85.15
	Slightly Warm	2	62.50
	Hot	3	31.00
	Total	121	
Q7T. How satisfied are you with the noise level in the indoor space?	cold	18	77.86
	cool	65	58.32
	slightly cool	20	49.85
	Neutral	13	76.08
	Slightly Warm	2	66.00
	Hot	3	23.50
	Total	121	

Test Statistics[a,b]

	Q3T. At this current time what is the feeling of temperature in your space?	Q4T. At this current time what is the feeling of humidity in your space?	Q5T. How satisfied are you with the level of fresh air in your space?	Q6T. How comfortable are you with day lighting in the lecture room workspace?	Q7T. How satisfied are you with the noise level in the indoor space?
Kruskal-Wallis H	4.413	5.136	9.399	15.299	13.027
df	5	5	5	5	5
Asymp. Sig.	.492	.400	.094	.009	.023

a. Kruskal Wallis Test

b. Grouping Variable: Q2T. How would you describe the thermal conditions in winter/ cold season?

Q4. Fourth Research Question

Kruskal-Wallis Test

Ranks

	Q1T. How would you consider the thermal sensation in the hot season?	N	Mean Rank
11a. Check your sitting position [Front row]	cool	1	20.50
	Slightly Warm	1	20.50
	Warm	2	20.50
	Hot	36	20.50
	Total	40	
11b. Check your sitting position [Central row]	cool	1	21.00
	Slightly Warm	1	21.00
	Warm	1	21.00
	Hot	38	21.00
	Total	41	
11c. Check your sitting position [Back row]	Warm	1	25.00
	Hot	36	20.00
	Total	40	
	Neutral	3	25.00

Test Statistics[a,b]

	11a. Check your sitting position [Front row]	11b. Check your sitting position [Central row]	11c. Check your sitting position [Back row]
Kruskal-Wallis H	.000	.000	1.258
df	3	3	2
Asymp. Sig.	1.000	1.000	.533

a. Kruskal Wallis Test

b. Grouping Variable: Q1T. How would you consider the thermal sensation in the hot season?

Q5. Fifth Research Question

Kruskal-Wallis Test

Ranks

	Q1T. How would you consider the thermal sensation in the hot season?	N	Mean Rank
Q8Ta.When is environmental thermal comfort most often a problem? Morning (before 11 am)	cool	2	63.00
	Neutral	3	63.00
	Slightly Warm	2	63.00
	Warm	4	63.00
	Hot	110	60.80
	Total	121	
Q8Tb.When is environmental thermal comfort most often a problem? Mid-day (11 am-2 pm)	cool	2	49.50
	Neutral	3	110.00
	Slightly Warm	2	49.50
	Warm	4	79.75
	Hot	110	59.40
	Total	121	
Q8Tc.When is environmental thermal comfort most often a problem? Afternoon (2 pm-5 pm)	cool	2	70.50
	Neutral	3	10.00
	Slightly Warm	2	70.50
	Warm	4	40.25
	Hot	110	62.80
	Total	121	
Q8Td.When is environmental thermal comfort most often a problem? Evening After 5 pm	cool	2	61.00
	Neutral	3	61.00
	Slightly Warm	2	61.00
	Warm	4	61.00
	Hot	110	61.00
	Total	121	
Q8Te. When is environmental thermal comfort most often a problem? Nighttime	cool	2	61.00
	Neutral	3	61.00
	Slightly Warm	2	61.00
	Warm	4	61.00
	Hot	110	61.00
	Total	121	

Test Statistics[a,b]

	Q8Ta.When is environmental thermal comfort most often a problem? Morning (before 11 am)	Q8Tb.When is environmental thermal comfort most often a problem? Mid-day (11 am-2 pm)	Q8Tc.When is environmental thermal comfort most often a problem? Afternoon (2 pm-5 pm)	Q8Td.When is environmental thermal comfort most often a problem? Evening After 5 pm	Q8Te. When is environmental thermal comfort most often a problem? Nighttime
Kruskal-Wallis H	.410	16.579	20.966	.000	.000
df	4	4	4	4	4
Asymp. Sig.	.982	.002	.000	1.000	1.000

a. Kruskal Wallis Test

b. Grouping Variable: Q1T. How would you consider the thermal sensation in the hot season?

APPENDIX VI (Arch. Studio IES-VE Model Report)

IES INTEGRATED ENVIRONMENTAL SOLUTIONS

Energy Model Output Report

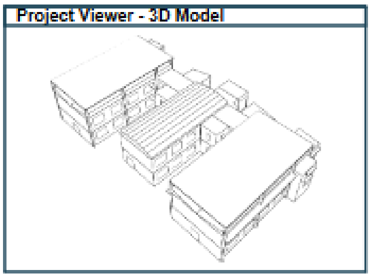
Project:	Baseline Report
Address:	STUDIO COMPLEX FACULTY OF ENVIRON SCIENCES
Climate File:	NGA_KB_Birnin.Kebbi.650030_TMYx.2007-2021.epw
Simulation:	TEST 1 AIRCOND.aps

Design Team:	RESEARCH STUDY TEA
Energy Analyst:	IESVE ENERGY REPORT
Owner:	FEDERAL UNIVERSITY E
Conditioned Area (m²):	1968.8564

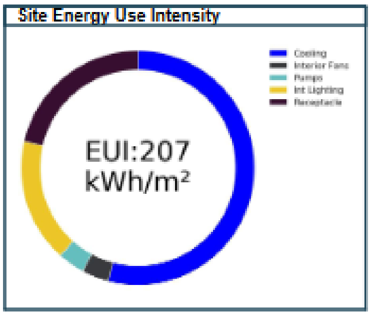
Annual Energy Consumption (kWh/m²/year) & CO2 kgCO2/m²/yr

Energy End Use	Site Energy	Source Energy	CO2 Emissions
Heating Fossil Fuel	0.0	0.0	0.0
Heating Electricity	0.0	0.0	0.0
Space Cooling	112.0	352.9	58.2
Fans Interior	7.7	24.2	4.0
Heat Rejection	0.0	0.0	0.0
Pumps	7.7	24.2	4.0
DHW Fossil Fuel	0.0	0.0	0.0
DHW Electricity	0.0	0.0	0.0
Interior Lighting	35.4	111.4	18.4
Exterior Lighting	0.0	0.0	0.0
Receptacle	44.2	139.2	22.9
Data Center	0.0	0.0	0.0
Cooking Fossil Fuel	0.0	0.0	0.0
Cooking Electricity	0.0	0.0	0.0
Elevators & Escalators	0.0	0.0	0.0
Refrigeration	0.0	0.0	0.0
Process	0.0	0.0	0.0
TOTAL (ex renewables)	206	651	107

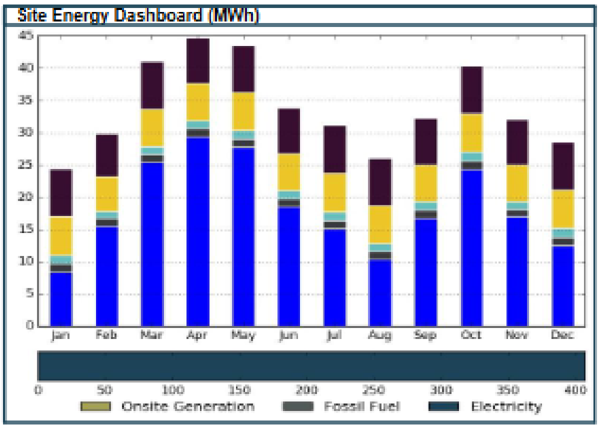
Project Viewer - 3D Model



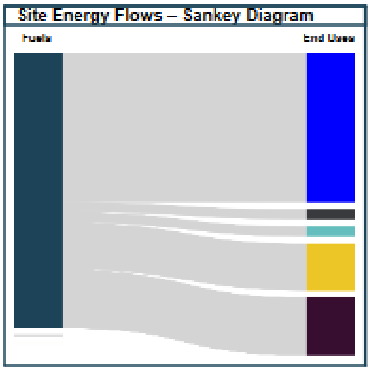
Site Energy Use Intensity



Site Energy Dashboard (MWh)



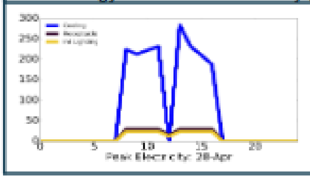
Site Energy Flows – Sankey Diagram

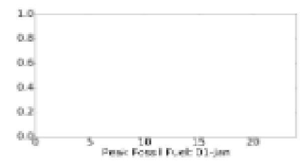


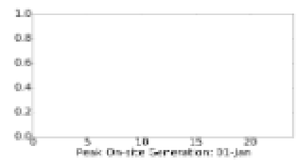
Annual Fuel Costs and Peak Demands

Fuels	Cost (£)	Peak Day	Peak Time	Peak Demand
Electricity	39,114.00	28-Apr	13:00	351.2 kW
Fossil Fuel	0.00	01-Jan	0:00	0.0 kW
Total	39,114.00	01-Jan	0:00	

Peak Energy Sources for Electricity (kW), Fossil Fuel (kW) and Onsite Power Generation (kW): Top 3 Contributors







Integrated Environmental Solutions 2019.3.0.0

APPENDIX VII (Classroom Complex IES-VE Model Report)

INTEGRATED ENVIRONMENTAL SOLUTIONS

Energy Model Output Report

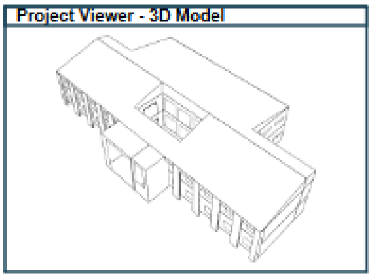
Project:	TEST 1 CLASSROOM COMPLEX FES, FUBK
Address:	CLASSROOM COMPL FACUL OF ENVIR STUDIES
Climate File:	NGA_KB_Birnin.Kebbi.650030_TMYx.2007-2021.epw
Simulation:	CLASS ROOM TEST 1 AC Vent.aps

Design Team:	THESIS REPORT UNIV
Energy Analyst:	CLASSROOM COMPL BL
Owner:	FEDERAL UNIVERSITY E
Conditioned Area (m²):	2380.8075

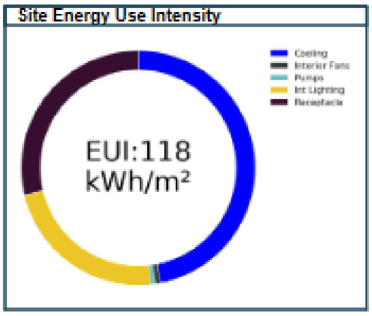
Annual Energy Consumption (kWh/m²/year) & CO2 kgCO2/m²/yr

Energy End Use	Site Energy	Source Energy	CO2 Emissions
Heating Fossil Fuel	0.0	0.0	0.0
Heating Electricity	0.0	0.0	0.0
Space Cooling	55.6	175.0	28.8
Fans Interior	0.8	2.5	0.4
Heat Rejection	0.0	0.0	0.0
Pumps	0.8	2.5	0.4
DHW Fossil Fuel	0.0	0.0	0.0
DHW Electricity	0.0	0.0	0.0
Interior Lighting	27.2	85.7	14.1
Exterior Lighting	0.0	0.0	0.0
Receptacle	34.0	107.2	17.7
Data Center	0.0	0.0	0.0
Cooking Fossil Fuel	0.0	0.0	0.0
Cooking Electricity	0.0	0.0	0.0
Elevators & Escalators	0.0	0.0	0.0
Refrigeration	0.0	0.0	0.0
Process	0.0	0.0	0.0
TOTAL (ex renewables)	118	372	61

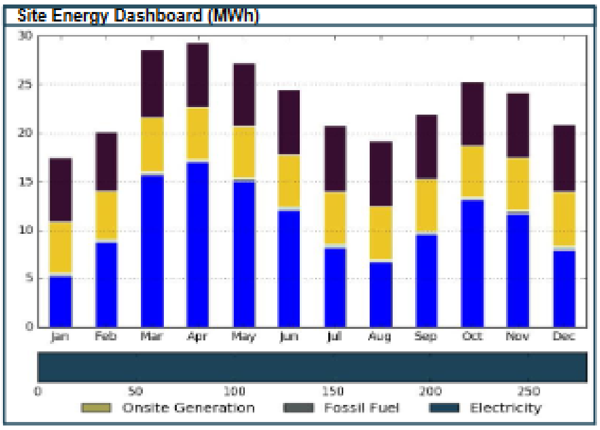
Project Viewer - 3D Model



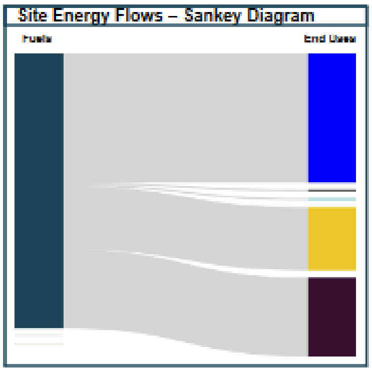
Site Energy Use Intensity



Site Energy Dashboard (MWh)



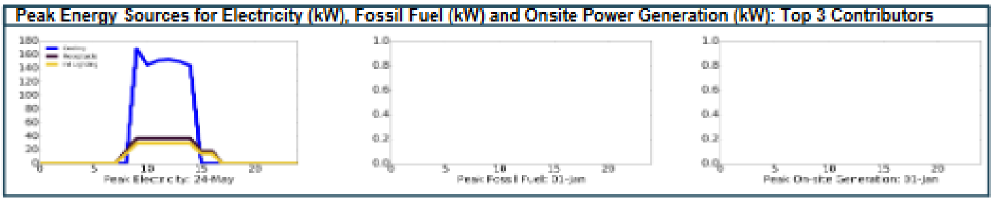
Site Energy Flows – Sankey Diagram



Annual Fuel Costs and Peak Demands

Fuels	Cost (£)	Peak Day	Peak Time	Peak Demand
Electricity	27,328.00	24-May	9:00	237.4 kW
Fossil Fuel	0.00	01-Jan	0:00	0.0 kW
Total	27,328.00	01-Jan	0:00	

Peak Energy Sources for Electricity (kW), Fossil Fuel (kW) and Onsite Power Generation (kW): Top 3 Contributors



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