DIMENSI: Journal of Architecture and Built Environment, Vol. 50, No. 2, December 2023 DOI: https://doi.org/10.9744/dimensi.50.2.53-68
ISSN 0126-219X (print) / ISSN 2338-7858 (online)

Building Optimisation Vis-À-Vis Solar Shading for Improved Comfort and Energy Efficiency in Classrooms

Mark Alegbe[1]*, Lawrence Chukwuemeka[2], John Lekwauwa Kalu[3], Amaka Eke-Nwachukwu[4]
[1,3,4] Department of Architectural Technology, Federal Polytechnic Auchi, 312101, Edo State, NIGERIA
[2] C.Lawrence and Partners, Maple Court, VON Garden City, Lugbe, FCT, Abuja, NIGERIA

Article Info:
Submitted: September 17, 2023
Reviewed: November 11, 2023
Accepted: November 30, 2023

Keywords:
building optimisation;
hybrid ventilation;
solar radiation.

Corresponding Author:
Mark Alegbe
Department of Architectural Technology, Federal Polytechnic Auchi, 312101, Edo State, Nigeria
Email: alegbemark@gmail.com

Abstract

Excessive solar radiation negatively affects classroom occupants' performance and thermal comfort, especially in buildings with West and East-facing glazed openings. This study utilises fixed external shading devices and triple-glazed low-emissivity windows to optimise a classroom building in Nigeria. Employing hybrid ventilation mode in EnergyPlus simulations, the optimised model shows a 44% reduction in discomfort hours, a 23% decrease in cooling load, and a 16% drop in energy demand compared to the original design. Comparative analysis of the optimised model with the as-built and West-East oriented classroom reveals a 16% and 10% reduction in energy consumption per conditioned area, along with 56 KWh/m² and 32 KWh/m² savings in cooling demand, respectively. Despite the effectiveness of fixed shading in curbing solar gains, occasional glare persists. This research underscores that shading alone may not fully meet thermal comfort requirements, emphasising the importance of building fabrics, building orientation and climate-sensitive design.

INTRODUCTION

The most critical consideration in the design of educational buildings is the provision of comfort conditions, primarily acoustic, visual and thermal conditions (Yener, 2002). Providing daylight in classrooms without the risks of discomfort glare is one of the aspects of a quality classroom environment (Viula, 2022). Solar gains in buildings contribute to the wellbeing of building occupants and play a role in the building's energy efficiency. As opined by (Alajmi et al., 2021), efficient building designs with the implementation of solar shading is an integral approach towards reducing energy consumption. The measure of solar radiation absorbed by the building envelope, particularly through direct solar gains via the windows and other glazed surfaces, significantly impacts the comfort level of the people in a building (Song et al., 2022). In classrooms, direct solar gains are found to increase the discomfort levels of occupants. A poorly managed light influx in classrooms can create discomfort glare that distorts students and teachers' abilities to study, learn and teach (Sok-Paupardin, 2021). Solar rays that are incident on walls, floors and writing or drawing surfaces increase discomfort levels and the indoor temperature of the spaces.

In the tropics, where high temperatures are experienced throughout the year, the shading of buildings is an essential strategy for reducing glare in the interior and solar gains by the building envelope. Studies show that excessive solar radiation is responsible for increased energy demand for cooling, and shading is considered a simple technique for retarding incident rays on building facades (Kamal, 2010, 2013). Glare control is a significant consideration in classroom design, and it should be avoided as much as possible by providing a means of limiting direct solar radiation (Yener, 2002). Designers must keep, especially transparent materials, away from the sun's path when dealing with buildings in the tropics (Al-Tamimi & Fadzil, 2011). Solar shading of buildings contributes to a significant reduction in the cooling load of the building (Littlefair, 2018; Prowler, 2016) and the intensity of solar glare (Girei et al., 2021). The cooling load reduction margin is especially significant where the building has a poor orientation. One of the advantages of solar shading is that it improves the indoor thermal comfort of occupants (Ishaq & Alibaba, 2017) and can be used to enhance illuminance levels in poorly lit spaces through careful design and installation (Ho et al., 2008). The exposure of the building envelope to the East and West trajectory of the sun subjects more surfaces to a potential solar gain (Soufiane et al., 2019) and difficulties in adopting the ideal control measure (Song et al., 2022). The impact of the sun on buildings varies with the time of the day and month of the year, influenced by two factors called the azimuth and altitude of the sun (Prowler, 2016). It is imperative to simulate the effect of shading on thermal comfort in buildings during the design stages (Ishaq & Alibaba, 2017), as the characteristics of a building and its shading devices influence energy savings (Bellia et al., 2013; Shahdan et al., 2018).

On the building design level, some of the strategies for building in hot-humid regions such as providing screened occupancy areas and patios, shaded outdoor areas, long narrow building floor plans, eliminating West-facing glazing and high performance or low emissivity glazing, as implied by (Architecture2030), if not correctly designed, positioned, or calculated for will be inadequate to mitigate the impacts of excessive solar gains in buildings. The benefits of shading devices depend on latitude and control methods (Littlefair, 2018); designing shading devices for solar control requires a great understanding of the sun's position at different times of the day. The greater the sun's angle above buildings, the higher its intensity and impact if the radiations are not diffused (Harris, 2018). The effect of the sun when it is high in the sky is more significant in buildings than when it is close to the horizon, as the rays are scattered by clouds, buildings, vegetation, and other surfaces along its path before reaching the building. Building characteristics such as orientation, layout, and thermophysical properties of the building envelope affect occupants' comfort (Girei et al., 2021). This study investigates the impacts of fixed solar shading devices on the indoor comfort and energy efficiency of a classroom building in a higher education institution in South-South Nigeria.

This study stems from concerns resulting from occupants' discomfort due to excessive glare and solar gains in a poorly oriented classroom block in Area III, Federal Polytechnic, Auchi. The result of this study is a proposed solution towards reducing indoor solar glare, solar gains, and energy consumption of the building. It aims to investigate the impact of fixed external solar shading devices on indoor comfort temperature and energy consumption in a classroom building in a hot-humid location. Specific questions to address are: a) How much does solar shading impact the comfort temperature in a classroom building? and b) How much energy can be saved by installing solar shading devices in a classroom? The objectives of this work are as follows.

1) To investigate the influence of fixed solar shading devices on glare reduction and operative temperature of classroom buildings
2) To examine the impact of solar shading on energy consumption in a classroom.

LITERATURE REVIEW

A comprehensive investigation into "Clever Classrooms", conducted by the Holistic Evidence and Design (HEAD) project and funded by the Engineering and Physical Sciences Research Council at the University of Salford, reveals compelling evidence regarding the influence of classroom design on academic performance. As asserted by (Barrett et al., 2015), the study emphasises the pivotal role of naturalness; light, temperature, and air quality, which collectively influenced half of the learning impact. Notably, 43% of the attributes associated with naturalness pertain to lighting quality, accentuating its significance in the educational environment. On indoor temperature levels, one of the strategies researchers worldwide have found to reduce the challenges of energy demand in buildings due to excessive solar gains is using passive design strategies such as external facade shading (Abdullahi et al., 2017). In the initial phases of architectural development, incorporating recessed window facades and implementing "brise-soleil," as conceptualised by Le Corbusier, emerged as sustainable strategies for mitigating solar heat gains in buildings. These design approaches effectively regulate indoor temperatures, particularly during overheating hours (Abdullahi et al., 2017; Kamal, 2013).

Historical exploration into solar incidences and shading techniques in buildings dates back to 1940 (Dubois, 1997), with different techniques, designs and materials employed by developers in various buildings across different climates worldwide. The design of shading devices is a complex and very challenging task (Bazazzadeh et al., 2021) as it involves a study of the material property of the device itself and the path of the sun's trajectory during different times of the day across the year (Al-Tamimi & Fadzil, 2011). In temperate climates, for example, the sun's altitude varies at divergent angles in a year, calling for care in positioning openings and installing shading devices during these varying periods. These variations in solar altitudes affect the intensity of solar radiation; as a result, shading may not always be required. Conversely, the sun's angle during peak and non-peak hours do not differ much in equatorial zones where the sun's intensity is highest (Wavomba, 2019).

Depending on the material and design, fixed shading devices can be very economical and simple to install. According to (Al-Masrani et al., 2018), fixed shading devices in tropical countries are cost-effective and easily installed. However, they pose the challenge of non-feasibility for changing climatic conditions during the year. Installing shading devices requires care as they impact the illumination level and ventilation rate in a building which can impede the comfort of occupants (Dubois, 1997). Some of the challenges of designing shading for indoor thermal comfort in the tropics is the extreme weather conditions experienced throughout the year (Guevara et al., 2021) and the suitability of shading devices to block low angle incident rays (Kamal, 2010). Shading in the tropics is a necessity (Littlefair, 2018) due to the high temperatures experienced, coupled with the fact that most buildings lack adequate insulation (Alegbe, 2022) to limit or control solar gains through walls. While the architect can easily control features such as the building characteristics and occupants' activity levels, the environmental factors that affect indoor thermal comfort are challenging to curtail (Girei et al., 2021).

The choice and position of a shading device are influenced by different parameters, which include the building orientation, surface or area to shade, cost and feasibility, and solar trajectory. A study conducted by (Bellia et al., 2014) (Figure 1) provides an overview of the different types of shading devices based on their positions. They are generally categorised as fixed and movable types, including overhangs, louvres, blinds, light-shelf, and fins in different alternatives.

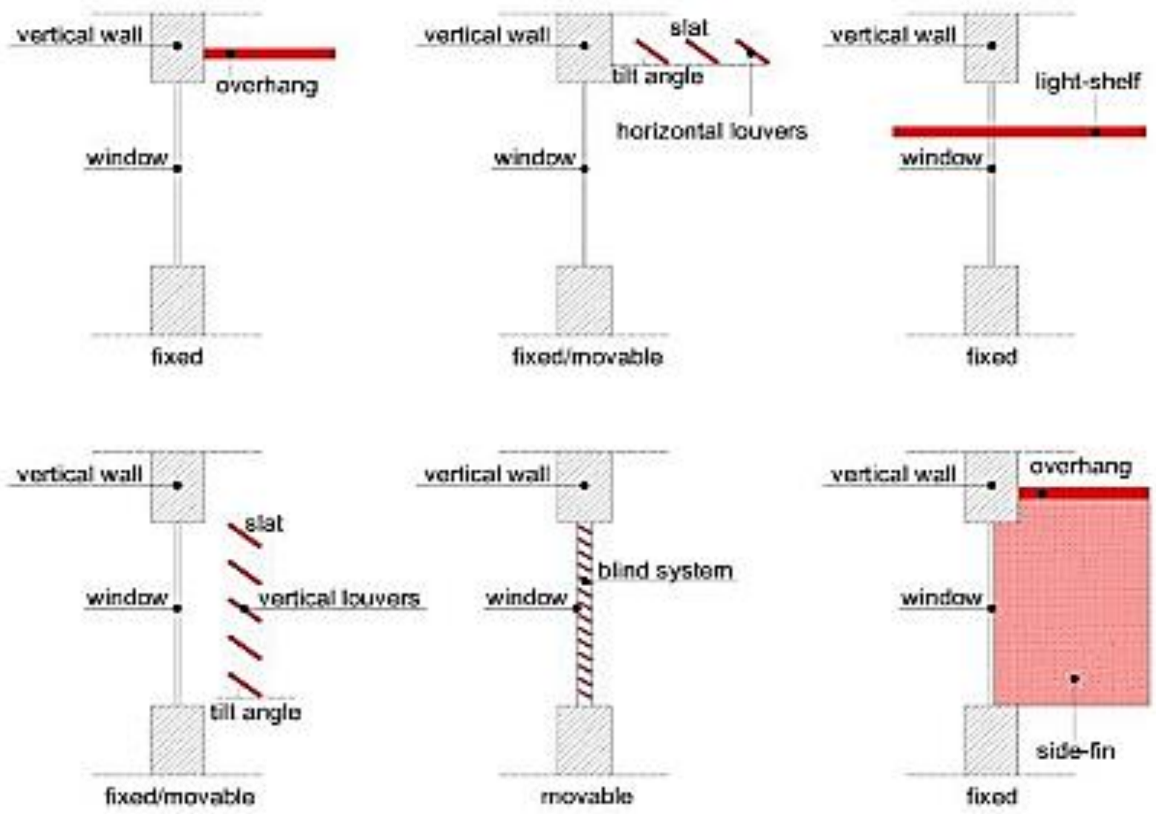


Fig. 1. Solar Shading Devices Source: (Bellia et al., 2014)

Selecting a shading device should be made with care not to affect the ventilation rate, illuminance level and visibility (Dubois, 1997). Compared to other shading devices, egg-crate shading has been found to reduce discomfort hours as it allows both shading and ventilation (Al-Tamimi & Fadzil, 2011). A comparative study by (Calama-González et al., 2019) compared two buildings; one with egg-crate shading and the other without. The conclusion suggests that egg-crate shading can reduce solar incidences on building facades by up to 50%. Some of the benefits of shading buildings are that it improves indoor comfort level and reduces discomfort glare while enhancing the energy efficiency of the building (Girei et al., 2021; Ishaq & Alibaba, 2017; Littlefair, 2018). Reducing buildings' energy consumption is a priority for climate change mitigation (ürge-Vorsatz et al., 2007). Buildings' energy efficiency is especially critical in Nigeria, where fossil fuels, despite the investment in renewable energy, still make up 25% of the country's energy mix (Transparency, 2020). Studies conducted by different authors in different climates show that energy consumption is reduced when buildings are shaded. An investigation by (Alajmi et al., 2021) in Kuwait for a mid-floor office building shows about 13-28% reduction in energy consumption using overhang and sided fins shading option, while with louvred shading, about 10%-21% savings was achieved. Additionally, a study by (Evangelisti et al., 2020) in Rome for an institution building shows 38.7% savings in energy consumption during summer with the installed shading devices but negligible savings in winter. As investigated by (Nikolaou & Meresi, 2021) in the different climates of Greece, horizontal concrete projection, horizontal non-transparent shutters, tilted aluminium light shelf and a combination of light shelf with external shutters were compared as shading alternatives in a typical classroom. The authors' conclusion suggests that although external blinds supply the best daylight distribution in the classroom, they also increase energy consumption and thermal discomfort.

In the warm summer climates of Palermo, southern Italy, the highest energy saving (20%) compared to other periods was obtained according to (Bellia et al., 2013) for a standalone office building. Furthermore, reviewed literature on thermal comfort studies in hot climates shows the sensitivity of occupants to changing indoor temperatures. Using the ASHRAE predicted mean vote, PMV and adaptive comfort models, as investigated by (Guevara et al., 2021), occupants in hot-humid location are inclined towards lower temperatures for indoor comfort. He further opined that while occupants used to hot-humid regions are sensitive to colder temperatures, those in colder climates are sensitive to hot temperatures. When temperatures are above 30ºc, it is unlikely that classroom users will feel comfortable in a dry climate (Calama-González et al., 2018). Moreover, (Porras-Salazar et al., 2018) is of the opinion that reducing classroom temperature for students acclimatised to hot climates can improve their performance and comprehension. The investigations by these authors show that operating air-conditioners in classrooms improved students' thermal comfort level by reducing the temperature from 30ºc in natural ventilation mode to 25ºc using air-conditioners. The examined works of literature present the significance of solar shading for indoor temperature reduction and improved thermal comfort of buildings in different climates. However, studies conducted in Nigeria for solar shading in classrooms are limited.

METHODS

The findings use quantitative data from simulations and statistical data analysis to reach a logical conclusion. The test classroom building was first identified using geographical coordinates on Google Maps. The coordinates were inputted in Meteonorm climate data generator to interpolate EnergyPlus Weather Files, EPW, for the location. The classroom design parameters were drafted in AutoCAD and imported into DesignBuilder (DB) energy modelling tool for accurate boundary establishment and building system modelling and simulation. The data generated from the DB EnergyPlus simulation tool were analysed, and the results are discussed in relevant sections of this work.

The study uses a three-step approach to compare the impacts of solar shading, building orientation and building fabric optimisation on the classroom's operative temperature and energy efficiency. Firstly, the study analysed the glare extent, operative temperature, and energy consumption of the case building. In the subsequent step, a shading device was designed and adopted through an in-depth solar path analysis. At the same time, the window glazings were optimised to reduce solar transmittance into the building. The last step compares the results of the first two steps to that of the case building, but with a West-East orientation. The comparison in the last step becomes imperative as the shading of windows performs differently based on their orientation (Alajmi et al., 2021; Alshamrani & Mujeebu, 2016; Lee et al., 2017). By default, most classroom buildings in Nigeria rely mainly on natural ventilation or passive systems for cooling (Ibhadode et al., 2017). The simulations under this study use a mixed-mode ventilation system that minimises energy efficiency by combining passive cooling through natural ventilation and cooling using ceiling-mounted fans powered by electricity from the grid. The concurrent technique in a hybrid ventilation strategy combines the effects of natural and mechanical ventilation means simultaneously (Brager et al., 2007).

Case Building

The building is a three-floor classroom block comprising typical spaces on each floor. A typical floor consists of three classrooms, access stairs on both ends and toilet facilities in the South. In this investigation, the classrooms on the ground floor are referred to as Studio One, Studio Two and Studio Three (Figure 2), with Studio One to the South and Studio Three to the North (see Figure 3.3 for building orientation). Similarly, studios four, five and six are located on the first floor, with studio four above studio one, while studios seven, eight and nine are on the second floor. The classroom block (Figure 3) is used by staff and students of the Architectural Technology Department of Federal Polytechnic Auchi for classroom activities like reading, writing, and drawing.

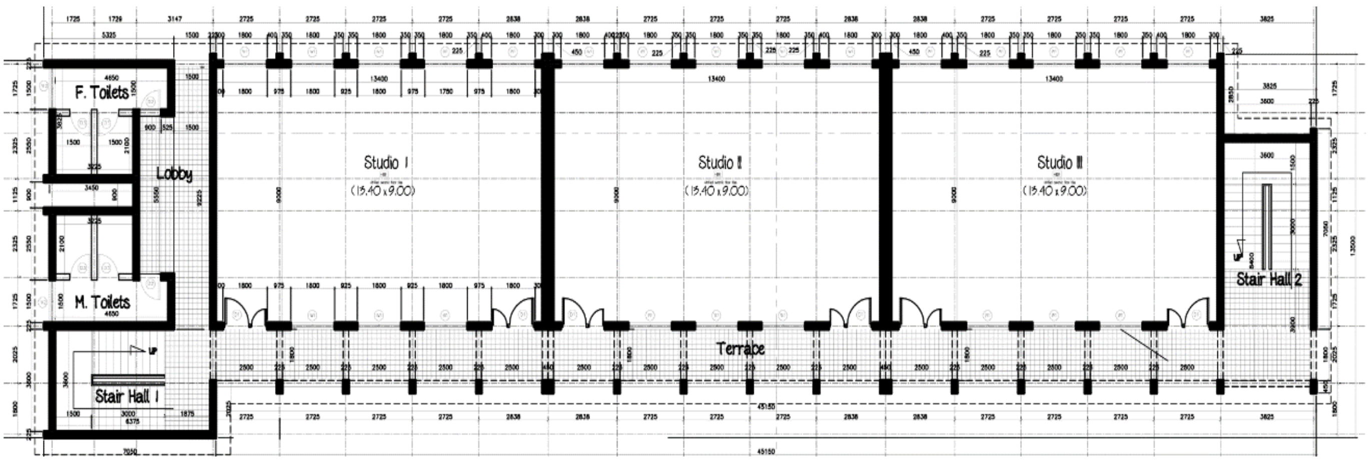


Fig. 2. Typical Floor Plan

Fig. 3. Approach View of the Classroom Block- Model (Left), Field Snapshot (Right)

Building Location and Typology

The building is in Area Three of the Federal Polytechnic Auchi, Edo State, Nigeria. It geographically lies at 7º03'13.0" N, 6º15'54.2" E (Figure 4). The building is oriented North-South, with a tilt of 17º from the North and the longer sides facing the East and West, respectively. The building is bounded to the North by a lecture theatre, to the East by two similar classroom blocks and to the West by small-scale residential developments.

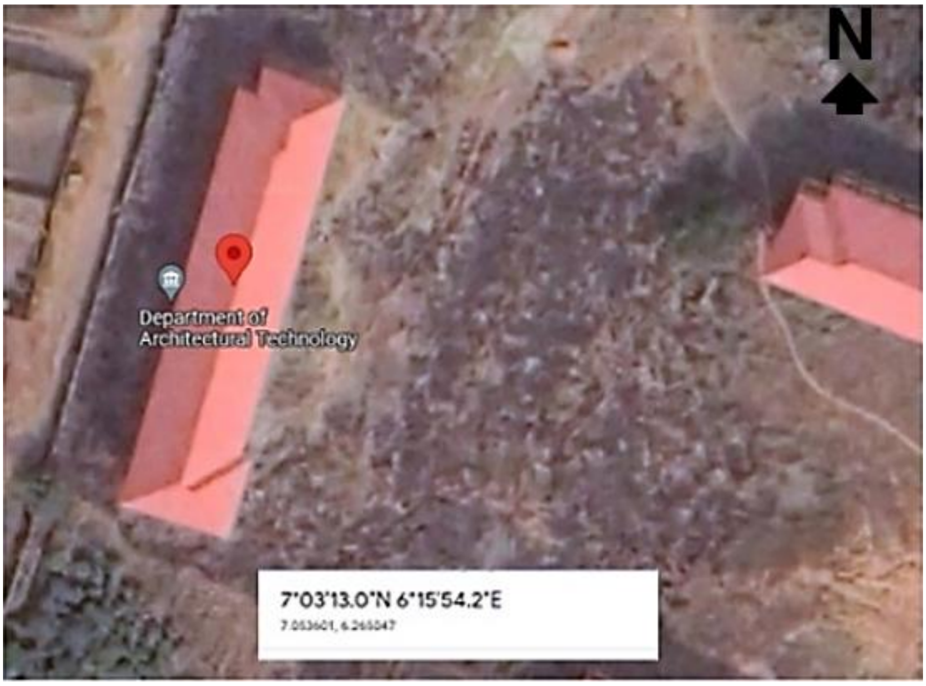


Fig. 4. Building Location (Source: Google Maps)

A hard ground texture of sand and soil particles surrounds the building, and surfaces like tar and concrete can reflect solar radiation into the building. Sand particles around building sites can also increase glare due to reflective particles (Girei et al., 2021). The building fabric consists of a 225mm hollow sandcrete block wall, plastered with cement-sand screed and painted with emulsion paint. The windows are 3mm single pane clear glass, while the roof is made of long-span corrugated aluminium roofing sheet. The design simulation parameters are highlighted in the result section.

Weather Data

The Koppen Geiger classification identifies the building in a tropical savanna climate (AW) (Mobolade & Pourvahidi, 2020). This climate is characterised by periods of a pronounced dry season and rainfall with high humidity. According to the classification by ASHRAE, the building is in climatic zone 1A, which is considered very hot and humid. With reference to Table 1 below, the highest mean monthly temperature is recorded in February with a dry bulb temperature of 27.8ºC. On the other hand, the lowest dry bulb temperature was recorded in August with a reading of 24.5ºC. Although high temperatures are recorded year-round (Figure 5), the climate is characterised by high relative humidity, up to 91%. The psychrometric chart in Figure 6 shows the relationship between dry bulb temperature and humidity ratio in this region.

Table 1. Weather Data Summary, Auchi

Data Source: MN7 999 WMO Station Number				Location: Auchi (Nigeria) Elevation: 197m	
	Monthly Average				
Months	**Dry Bulb Temp.** (ºC)	**Rel. Hum.** (%)	**Global Hor. Rad.** (KWh/m²)	**Wind Speed** (m/s)	**Wind Direction** (Degrees)
Jan.	27.1	65	162	1.6	220
Feb.	27.8	73	140	1.8	190
Mar.	27.5	81	172	2.0	190
Apr.	26.8	87	174	1.8	210
May	26.2	88	170	1.5	200
Jun.	25.2	91	155	1.6	200
Jul.	24.7	88	163	1.9	210
Aug.	24.5	88	153	2.0	220
Sep.	24.7	91	158	1.6	180
Oct.	25.4	88	171	1.3	220
Nov.	26.3	87	170	1.4	200
Dec.	26.7	73	159	1.6	230

Source: Meteonorm, DesignBuilder

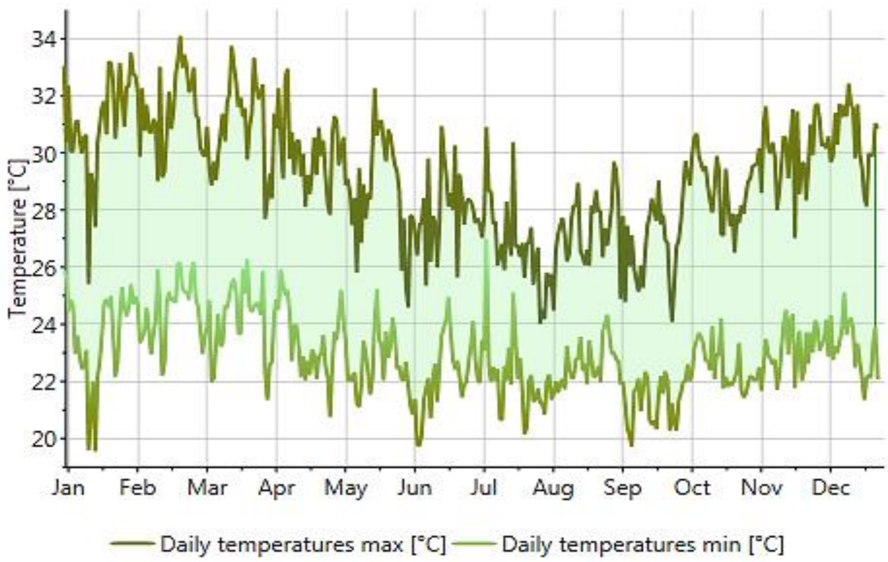


Fig. 5. Minimum and Maximum Daily Temperatures (Source: Meteonorm

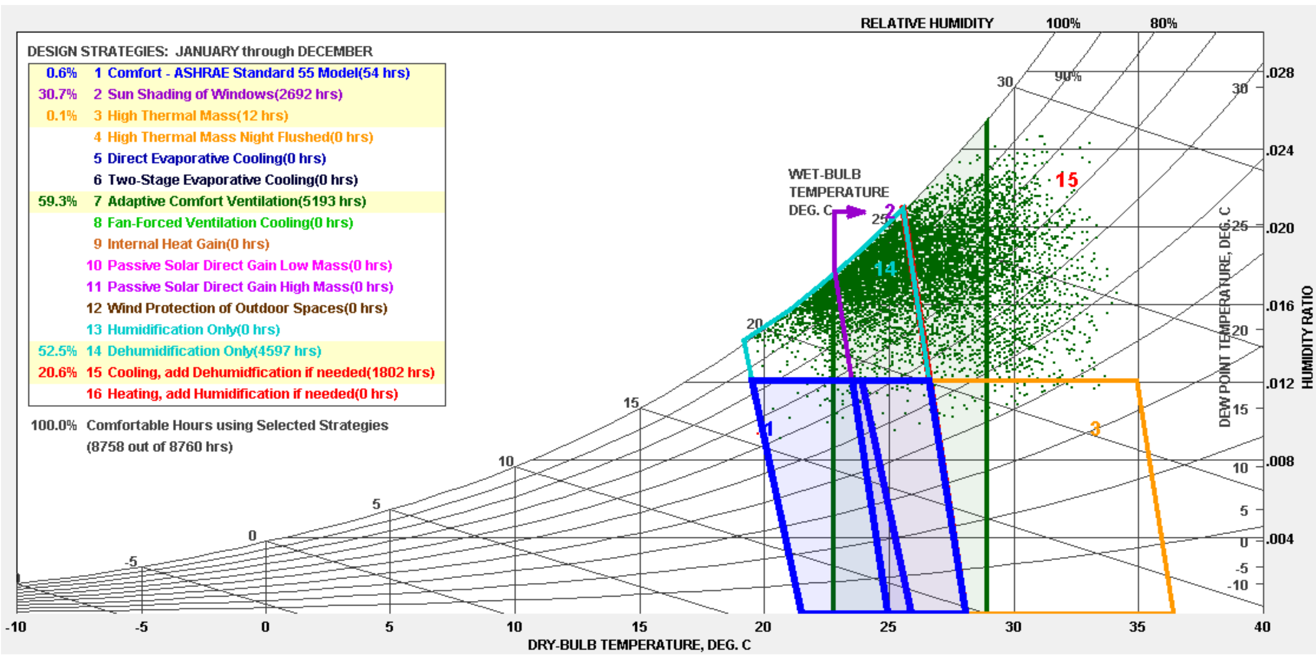


Fig. 6. Psychrometric Chart for the Location

Solar Path

The building location is close to the equator; thus, the sun's exposure is felt throughout the year. However, there is a slight difference between the solar peak period when it is high above the sky and when it is lowest. A solar study conducted for this location shows a difference of 26º between the peak and lowest altitudes. The sun's trajectory is from East to West and slightly towards the South. Figure 3.6 below shows that the highest altitude of the sun occurs on the 5th of April at approximately 84º, while the lowest altitude is at 58º on the 18th of December. This study is significant for the design and positioning of solar shading devices. Latitude affects the efficiency of solar shading. It is found that it is more efficient in heating-dominated regions to install shading devices that can be removed during winter when solar gains are ultimately beneficial (Dubois, 1997). Unlike in cold climates where solar gains are essential during wintertime but shaded during summertime, shading buildings all year round from direct solar radiation is a crucial design strategy in sub-Saharan Africa.

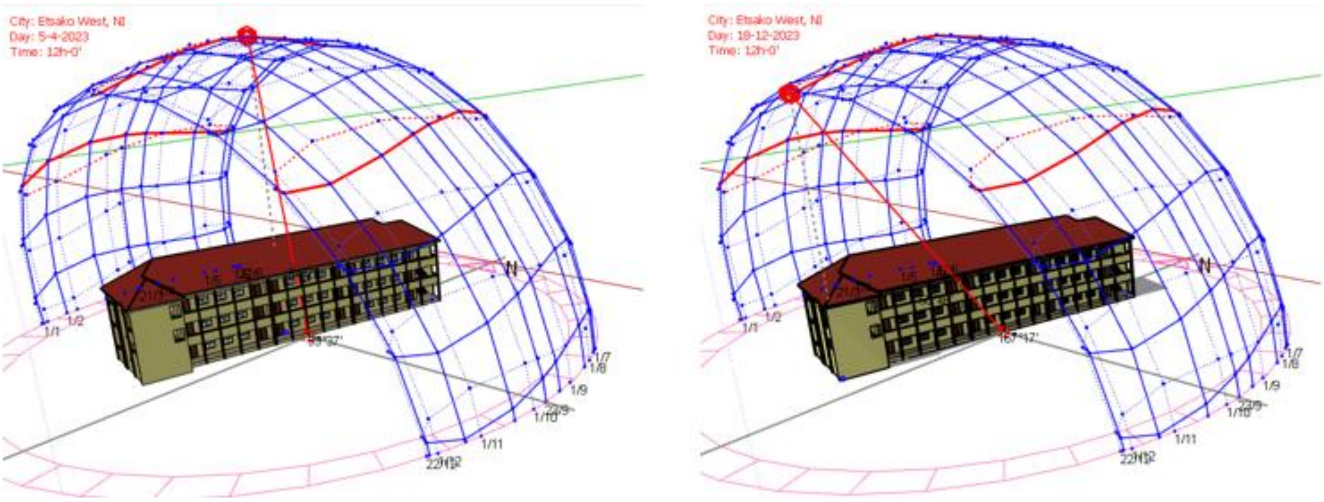


Fig. 7. Solar Path around Case Building (Source: Curic Sun, Sketchup)

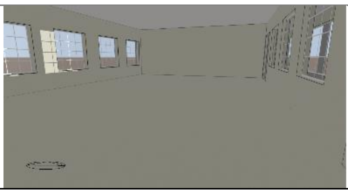
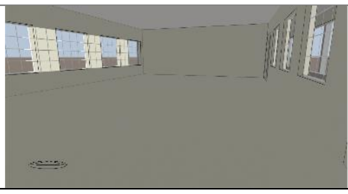
RESULTS

Solar Gains

The average hourly direct normal radiation in the building is between 181 and 410 Wh/m² yearly. These high radiation values contribute to an increased indoor temperature of the building. The simulation shows that on the 18th of December when the sun's altitude is lowest, the direct solar radiation into the building extends to the middle of the classrooms, causing excessive glare. On a typical day in December, there is a direct solar incidence for approximately seven hours between 6:23 a.m. and 9:12 a.m. from the East and between 2 p.m. and 6 p.m. from the West. Outside these hours, the sun is shaded by the balconies and patios or directly over the roof. These occurrences are primarily on horizontal surfaces like floors and drawing or writing tables, causing high discomfort during occupied hours.

Similarly, on a typical day in April when the sun is at its peak, there is a direct solar incidence in the building for about seven hours, between 6:10 a.m. and 9 a.m. from the East and between 2 p.m. and 6 p.m. from the West. The incidences on the interior surfaces for these solar periods are shown in Table 2, while the sun's position at noontime each month is presented in Table 3.

Table 2. Solar Incidences in a Typical Classroom

	Month	
	April 84º	**December** 58º
EAST		

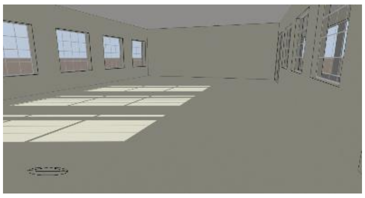
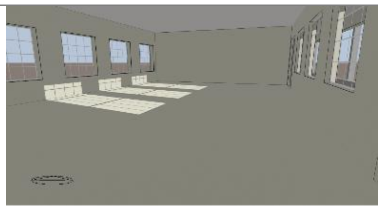
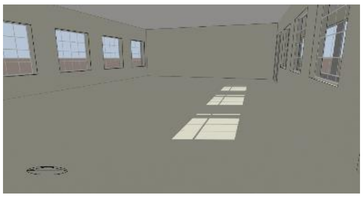
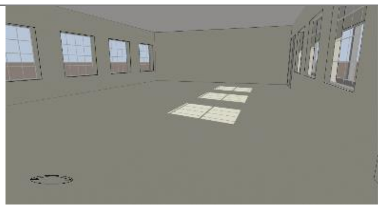
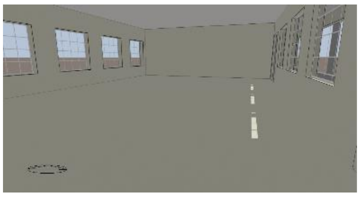
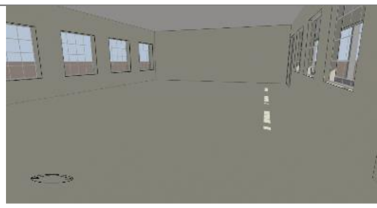
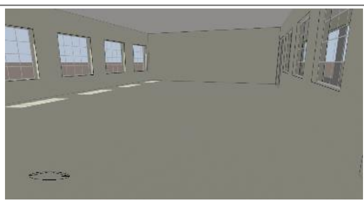
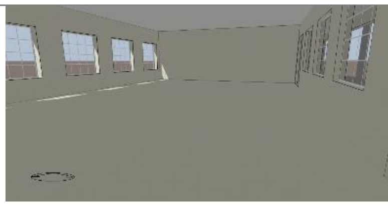
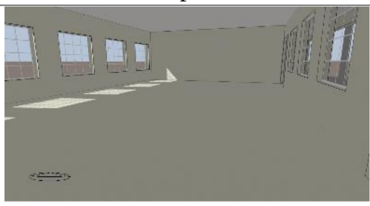
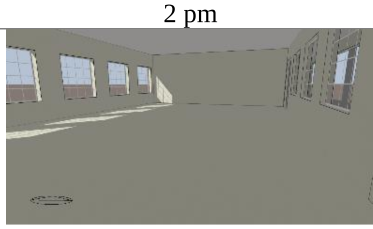
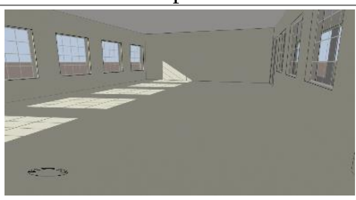
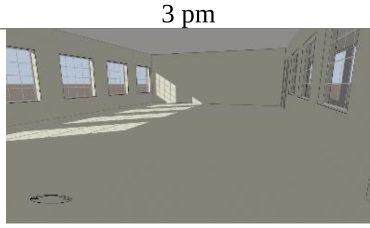
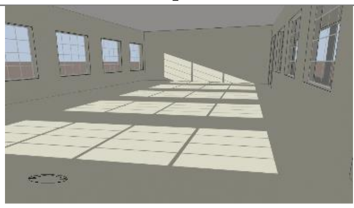
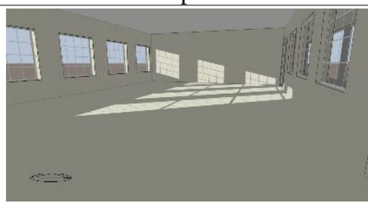
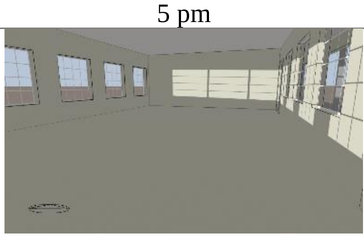
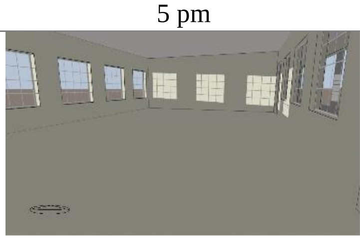
	6:10 am	6:23 am
	 7 am	 7 am
	 8 am	 8 am
	 9 am	 9 am
WEST	 2 pm	 2 pm
	 3 pm	 3 pm
	 4 pm	 4 pm
	 5 pm	 5 pm
	 6 pm	 6 pm

Table 3. Annual Solar Trajectory around the Building

	15th Day of the Month at Noontime											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Altitude	61^{0}	70^{0}	79^{0}	83^{0}	76^{0}	72^{0}	74^{0}	81^{0}	81^{0}	71^{0}	62^{0}	58^{0}
Azimuth	171^{0}	171^{0}	155^{0}	66^{0}	30^{0}	19^{0}	17^{0}	36^{0}	117^{0}	147^{0}	158^{0}	166^{0}

Case Building

The modelled case building has occupied and unoccupied floor areas of 1706.8m^2 and 677.8m^2, respectively. The building's total occupied volume is 6448.2m^3, while its unoccupied volume is 1458.1m^3. A metabolic factor of 1.0 was set for the simulation with a minimum fresh air of 3.54 l/s per person and an airtightness of 1.0 ac/h. Other thermophysical properties of the case building are highlighted in Table 4 below. The operative temperatures of the as-built building block, floors and classrooms are outlined in Table 5

Table 4. Thermophysical Properties of Case Building

U-Value -Wall (W/m^2-k)	U-Value- Ground Floor (W/m^2-k)	U-Value- Upper Floor (W/m^2-k)	U-Value –Roof (W/m^2-k)	Glazing Type	U-Value- Glazing (W/m^2-k)
2.468	2.279	1.697	2.930	3mm Single Pane Clear Glass	5.894

Table 5. Mean Operative Temperature

	Mean Operative Temperature of Building Block (^{o}c)											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
As-Built	29.50	29.65	29.84	29.59	29.36	28.66	28.52	28.18	28.34	29.16	29.43	29.49
	Mean Operative Temperature As-Built Model (^{o}c)											
Ground Floor	27.13	27.24	27.37	27.17	27.00	26.38	26.35	26.10	26.15	26.75	26.99	27.07
First Floor	29.98	30.14	30.32	30.05	29.80	29.12	28.98	28.64	28.88	29.66	29.87	29.97
Second Floor	31.38	31.57	31.83	31.54	31.28	30.47	30.23	29.79	30.07	31.08	31.42	31.42

	Mean Operative Temperature of Classrooms (^{o}c)								
	Studio One	Studio Two	Studio Three	Studio Four	Studio Five	Studio Six	Studio Seven	Studio Eight	Studio Nine
As-Built	26.68	26.75	26.82	29.46	29.60	29.70	30.43	30.61	32.08

Optimised Model

The optimisation technique applied to the existing building block is in the glazing and installation of fixed external shading devices. (Yener, 2002) suggests that solar control can be provided by using fixed or adjustable shading devices that can be placed in the interior or exterior of the windows. The technique can significantly reduce the glare effect, indoor temperature, and building energy consumption. While other building properties remain the same, the classroom window glazings were replaced with 13mm air triple low-emissivity 3mm clear glass with a U-value of 0.982 W/m^2-k and direct solar transmission of 0.358 W/m^2-k. Views of the optimised model are represented below.

Fig. 8. Optimised Model, Isometric View (Left), Front View (Right)

Limiting solar gains calls for the shading of surfaces that absorb direct and indirect solar radiation (Al-Tamimi & Fadzil, 2011). The installed external shading device is made of treated timber and fastened to the exterior building walls and columns. It is a combination of an overhang and 35mm diameter vertical timber fins spaced at 10 mm to limit glare whilst allowing ventilation. The extent of the shading device was evaluated using the solar chart in climate consultant (Figure 9) and the solar path in DesignBuilder. Figure 10 shows the solar radiation in a typical classroom during solar peak and dip hours in April and December. The impact of the optimised model on indoor operative temperatures of the building and classrooms is presented in Table 6.

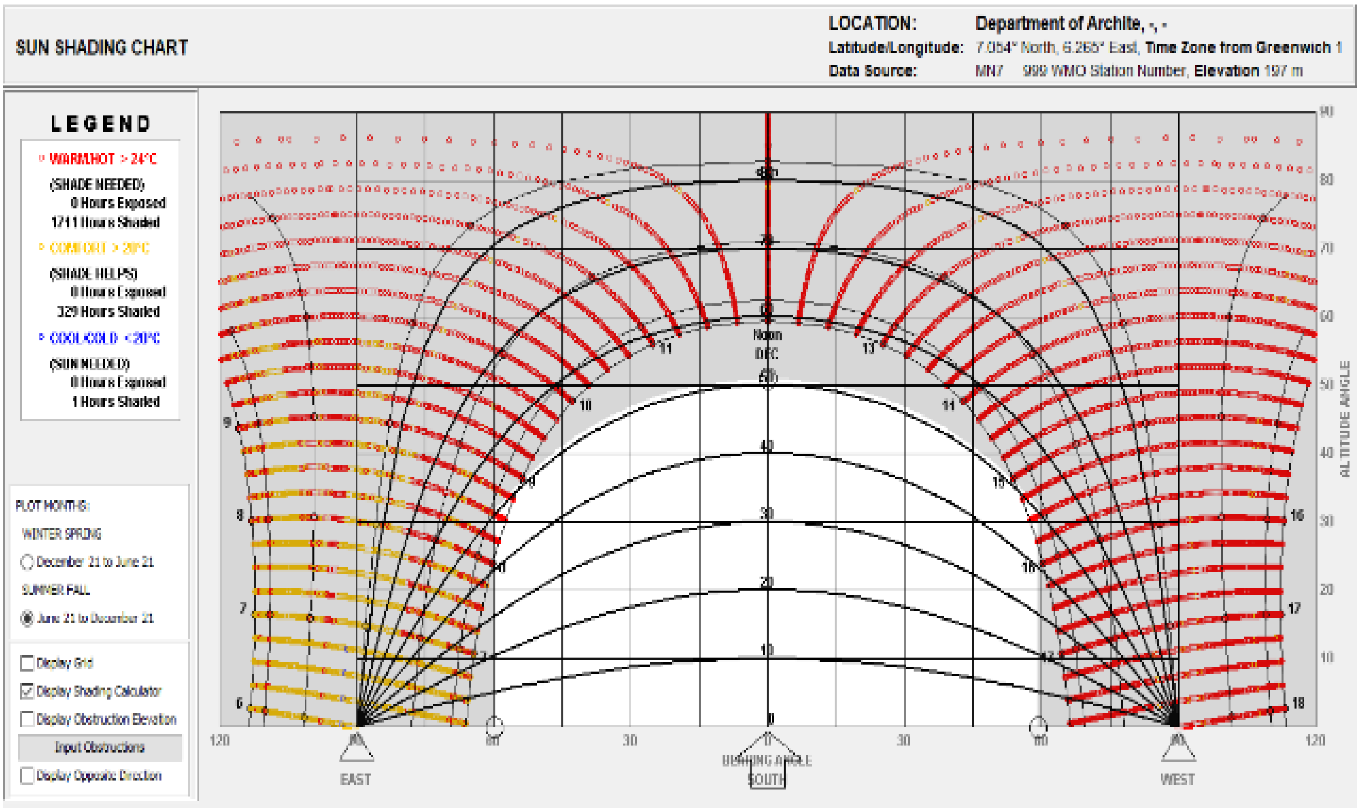


Fig. 9. Solar Shading Chart for Building Block (Source: Climate Consultant)

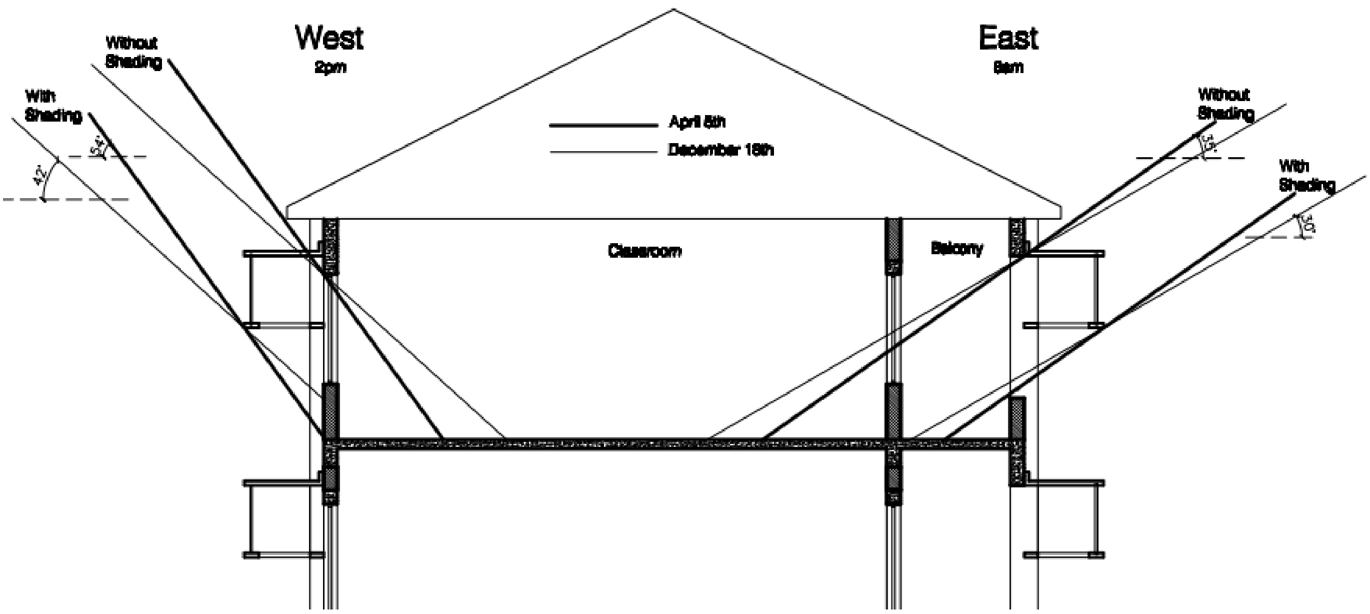


Fig. 10. Solar Radiation in a Typical Classroom

Table 6 Mean Operative Temperature - Optimised Model

Mean Operative Temperature of Building Block (ºc)												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Optimised Model	28.36	28.59	28.65	28.27	28.03	27.34	27.26	26.93	27.06	27.66	28.04	28.28
Mean Operative Temperature Optimised Model (ºc)												
Ground Floor	26.01	26.15	26.16	25.83	25.71	25.14	25.16	24.92	24.95	25.33	25.67	25.9
First Floor	28.76	29	29.03	28.63	28.37	27.12	27.63	27.3	27.43	28.04	28.38	28.67
Second Floor	30.31	30.62	30.75	30.29	30.02	29.17	28.98	28.56	28.8	29.61	30.07	30.27

Mean Operative Temperature of Classrooms (ºc)									
S/No	Studio One	Studio Two	Studio Three	Studio Four	Studio Five	Studio Six	Studio Seven	Studio Eight	Studio Nine
Optimised Model	25.41	25.39	25.51	28.05	28.09	28.22	29.28	29.39	30.59

DISCUSSION

Solar shading in the tropics is essential for indoor comfort, unlike in temperate regions where solar shading is not always required (Littlefair, 2018). The choice and especially location of the shading device is not only to limit solar gain through the building but also designed to, in addition to window shading, shade part of the exposed walls without compromising visibility. A combination of fixed external shading devices and low-emissivity triple glazing was used as the technique to improve the overall performance of the classroom building block. Solar shading was used to minimise solar gains and glare in the building, especially during occupied hours, between 8:00 am and 5:00 pm, while the glazing was used to reduce direct solar transmission into the building. The results of the optimised model were compared with the case building and a classroom block with proper (West-East) orientation. The results of the simulated buildings show that compared to the ground floor, it is hotter on the upper floors, while the energy consumption is the least for the optimised model with installed shading devices.

Glare Control

On the assumption that classroom doors are closed during occupied hours, the results of the simulation show that without the installed solar shading device, the as-built model allows for glare discomfort due to direct solar gains through the windows for approximately seven hours on a typical day in December or April. About 57% of this period is due to solar gains from openings on the West. This is not surprising as studies have shown that the average solar heat gain from exposed walls to the East and West is 1.4 times greater than those on the North and South (Arman, 2019). Due to the sun's low angle during rising and setting hours, the shading devices do not allow for total glare protection, although it has reduced solar penetration level by about 71%. During occupied hours, there is no glare discomfort from the East. Direct solar penetration occurs only for approximately one hour from the West between 4 pm and 5 pm on a typical day.

Operative Temperature Variance

(Alajmi et al., 2021) opined that the North orientation is the least considered area for shading in the northern hemisphere, where the sun's trajectory is slightly to the South. Similarly, in this region, South-facing rooms, compared to North-facing, are more exposed to solar gains. However, the classrooms towards the North in this experiment have more solar gains than those in the middle and to the South. This is owed to the building's configuration, as classrooms towards the North are not shaded by other ancillary spaces compared to those at the South, shaded by toilet facilities. Figure 11 shows the mean operative temperature for the building blocks during the year. Accordingly, the optimised model has the least operative temperature of 26.93ºc in August; it is 1% and 4% less than the W-E and as-built models, respectively. Since shadings are particularly effective during the hottest period of the year (Arman, 2019), an investigation In February and March, when the highest operative temperature was recorded, shows that the optimised model accounts for the least temperature of 28.65ºc, which is 2.5% and 4% less than the recorded temperature for the W-E and as-built models respectively.

The building optimisation technique results in a more improved indoor comfort by narrowing the classrooms' comfort range. In the case building, the comfort range was between 23ºc and 29ºc, while it narrowed down to between 23ºc and 27ºc in the optimised model. With reference to the comfort temperature of 28ºc for buildings in the tropics, as asserted by (Jegede & Taki, 2021; Ogbonna & Harris, 2008; Siti Handjarinto & Veronica I, 1998), it was found that only the ground floor; studios one, two and three satisfy comfort requirements in terms of operative temperature (Figure 12). Furthermore, there is a disproportionate increase in hours above the comfort temperature with increasing floor levels and spaces towards the North, it is observed that the operative temperature increases slightly with increased floor level across the models.

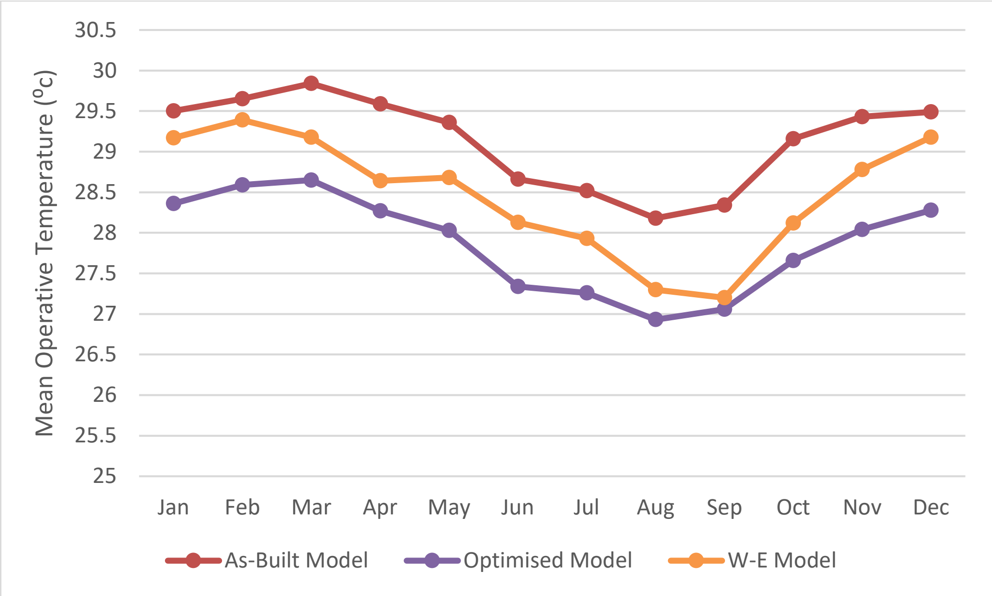


Fig. 11. Mean Monthly Operative Temperature of Building Blocks

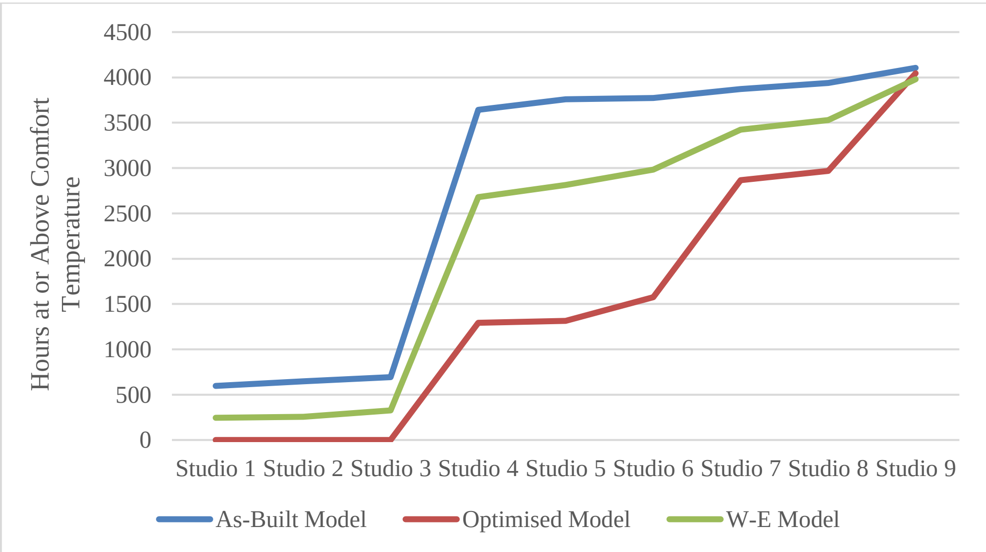


Fig. 12. Hours above 28ºc

Energy and Lighting Demand

Solar gains into the building are increased with a more exposed surface area due to poor orientation of the building to the sun's path. More than 40% of the total glazing in the case building is exposed to the West. Although the energy performance and cooling load of the building with the W-E orientation is better than the as-built model, the optimised model, with a poor orientation, accounts for the least energy consumption. This implies that the performance of a poorly sited building can be enhanced by applying appropriate optimisation measures. Similar to investigations conducted by (Bellia et al., 2013), a building with its length along the North-South axis would have a poor energy efficiency coefficient.

Where the illumination level in a room is poor, installing fixed solar shading can result in a further lower lux level and increase the lighting load of the building (Yener, 2002). While the general interior lighting demand for the building remains unaffected at 100.93 KWh/m², the optimised model compared to the case building results in 16% savings in energy per total building area and approximately 23% in cooling load per conditioned building area. Also, compared to the W-E model, the optimised model has about 10% and 14% reduction in energy and cooling load per building area, respectively (Figure 13). Furthermore, the sensible cooling load of the models show a significant difference in potential cooling energy. Compared to the as-built and W-E models, the optimised model shows a difference of 29% and 19% on the zone sensible cooling load, respectively. According to (ASHRAE, 2005), the sensible cooling load defines the amount of heat needed to be removed by the cooling system in a conditioned space.

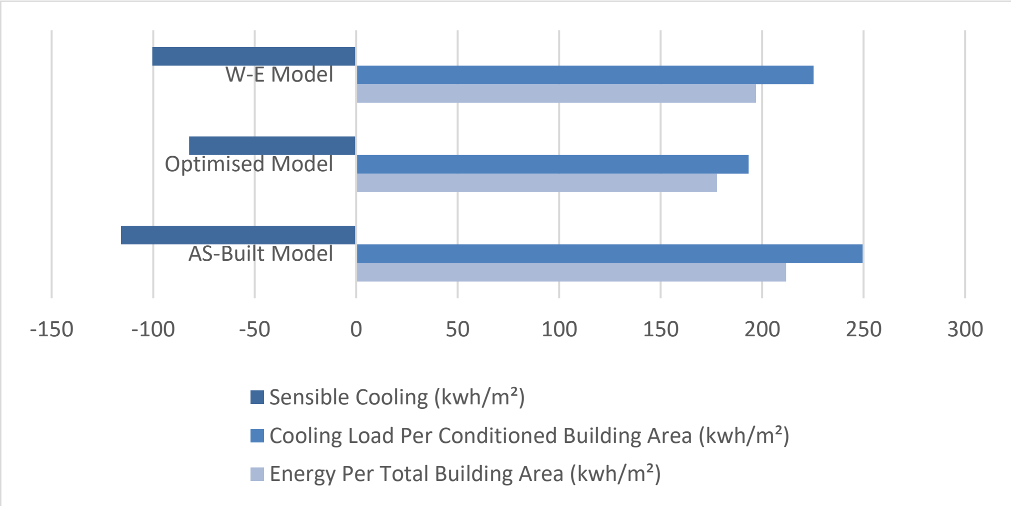


Fig 1. Buildings' Energy Load

CONCLUSION

Solar penetration in buildings has its benefit on occupants' comfort and wellbeing. It also impacts the overall energy consumption of the building through reduced cooling demand (Girei et al., 2021; Littlefair, 2018). Solar gains are highly in demand in climates with vast seasonal differences when the temperature is low but highly protected during peak temperature periods. Solar gain in a building is hardly desired in a Sub-Saharan African climate like Nigeria, where thr temperature in certain regions can be as high as 35ºc. As a result, solar shading, which affects building energy use through the regulation of conduction-convection processes, is employed (Dubois, 1997).

The orientation of a building, its fabric composition and design strategies play a vital role in limiting solar gains in building for a better indoor environment. Where a building is poorly oriented in a climate with year-round hot temperatures, it is challenging to limit solar gains. The glare discomfort level, indoor temperature, and cooling load will increase in classrooms with a high level of direct solar penetration. This study uses an optimisation technique through solar shading and glazing enhancement to control solar gains in a classroom block in Area Three in Federal Polytechnic Auchi.

The availability of building simulation tools makes it possible to accurately measure and calculate the impacts of a range of shading devices (Wah et al., 2008). The study uses Climate data from Meteonorm weather generator, solar path study and EnergyPlus simulation algorithm in DesignBuilder to arrive at a suggestive conclusion. The simulations were conducted using the ASHRAE adaptive comfort model, ideal for building simulation for naturally ventilated buildings with little or no mechanical cooling (ASHRAE, 1992). A hybrid or mixed-mode method of ventilation that combines passive and mechanical means was employed in the simulations. This strategy is mainly operational, where thermal comfort benefits with a reduction in energy demand are prioritised (Brager et al., 2007). In tropical buildings, passive cooling measures are not always adequate to improve comfort levels; there is a need to introduce active cooling systems for better comfort sensation (Girei et al., 2021).

The results, which compare the as-built, optimised and West-East (W-E) orientation building blocks, show that the optimised model accounts for the least energy consumption per conditioned building area, which is approximately 16% and 10% less than the as-built and W-E buildings, respectively. The cooling demand for the optimised model is also the least, with savings of up to 56 KWh/m² compared to the as-built model and 32 KWh/m² compared to the W-E model. Although the fixed shading device accounts for a significant reduction in direct solar gains in the building, there are still some glare levels for about an hour from the low setting sun from the West glazing.

Shading devices in buildings can reduce illumination levels (Wah et al., 2008; Yener, 2002), and poorly managed light influx in classrooms can affect teaching and learning (Sok-Paupardin, 2021). Solar shading, in combination with triple-glazed windows, with a 57% reduction in direct solar transmission value, compared to the single glazing of the existing building, amounts to a lower indoor temperature in the classrooms. On average, the optimised model accounts for a 44% reduction in hours above the comfort temperature of 28ºc annually, compared to the as-built model, and a 31% reduction against the W-E model. However, the optimisation of the as-built model could only bring the classrooms on the ground floor, i.e., studios one, two and three, within the comfort zone all through the year, classrooms on the upper floors, especially on the second floor, though with very little discomfort glare will have to resort to only mechanical means of ventilation to attain desired thermal comfort temperature. The opinion shared by the author in this regard is in tandem with claims by (Arman, 2019), who opined that although solar shading devices reduce the risks of overheating, they are insufficient to fulfil thermal comfort requirements on their own. While this study suggests effective solutions for reducing glare, indoor temperature and building energy use in a poorly oriented building, further investigation is required in assessing the lux level of the building with the installed shading devices.

ACKNOWLEDGEMENT

The authors acknowledge the support of students and staff of the Department of Architectural Technology, Auchi Polytechnic, Auchi, Edo State, Nigeria.

REFERENCES

Abdullahi, M., Kandar, M. Z., Wah, L., Kamal, M., & Ashiru, A. (2017). Exploratory Survey of Recessed Window Façade Shading in Johor Bahru Malaysia. C*hemical Engineering Transactions*, ***56***, 1807-1812. https://doi.org/https://dx.doi.org/10.3303/CET1756302

Al-Masrani, S. M., Al-Obaidi, K. M., Zalin, N. A., & Aida Isma, M. I. (2018). Design optimisation of solar shading systems for tropical office buildings: Challenges and future trends. *Solar Energy*, ***170***, 849-872. https://doi.org/10.1016/j.solener.2018.04.047

Al-Tamimi, N. A., & Fadzil, S. F. S. (2011). The Potential of Shading Devices for Temperature Reduction in High-Rise Residential Buildings in the Tropics. *Procedia Engineering*, ***21***, 273-282. https://doi.org/10.1016/j.proeng.2011.11.2015

Alajmi, A., Aba-alkhail, F., & ALAnzi, A. (2021). Determining the optimum fixed solar-shading device for minimizing the energy consumption of a side-lit office building in a scorching climate. *Journal of Engineering Research*, ***9***(2), 320-335. https://doi.org/10.36909/jer.v9i2.10773

Alegbe, M. (2022). Comparative Analysis of Wall Materials Toward Improved Thermal Comfort, Reduced Emission, and Construction Cost in Tropical Buildings. [Conference Proceedings]. 11th Masters Conference: People and Buildings University of Westminster, London, United Kingdom. https://eprints.soton.ac.uk/471027/

Alshamrani, O., & Mujeebu, M. A. (2016). Effects of shading strategy and orientation on energy performance of school building. *Journal of Architecture and Planning*, ***28***(1), 129-141. https://cap.ksu.edu.sa/sites/cap.ksu.edu.sa/files/imce_images/jap_ksu_jan2016_en1.pdf

Architecture2030. A Resource for the Design of Zero-Carbon, Adaptable and Resilient Built Environments Worldwide Architecture 2030. Retrieved 9th March, 2023 from *http://2030palette.org*

Arman, H. (2019). Assessment of solar shading strategies in low-income tropical housing: the case of Uganda. *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*, ***172***(6), 293-301. https://doi.org/10.1680/jensu.17.00072

ASHRAE. (1992). Standard 55- Thermal Environmental Conditions for Human Occupancy. American Society of Heating, Refrigerating and Air conditioning Engineers, *ASHRAE*. Retrieved 13th March, 2023 from https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environment-conditions-for-human-occupancy

ASHRAE. (2005). ASHRAE Guideline 2-2005, Engineering Analysis of Experimental Data. *The American Society of Heating, Refrigerating and Air-Conditioning Engineers*. Retrieved 15th March, 2023 from https://webstore.ansi.org/preview-pages/ASHRAE/preview_ASHRAE+Guideline+2-2010.pdf

Barrett, P. S., Zhang, Y., Davies, F., & Barrett, L. (2015). *Clever classrooms: Summary report of the HEAD project*. University of Salford. Retrieved 27th November from https://desis.osu.edu/seniorthesis/index.php/2022/10/05/clever-classrooms-summary-report-of-the-head-project/

Bazazzadeh, H., Świt-Jankowska, B., Fazeli, N., Nadolny, A., Safar ali najar, B., Hashemi safaei, S. S., & Mahdavinejad, M. (2021). Efficient Shading Device as an Important Part of Daylightophil Architecture; a Designerly Framework of High-Performance Architecture for an Office Building in Tehran. *Energies*, ***14***(24), 8272. https://doi.org/10.3390/en14248272

Bellia, L., De Falco, F., & Minichiello, F. (2013). Effects of solar shading devices on energy requirements of standalone office buildings for Italian climates. A*pplied Thermal Engineering*, ***54***(1), 190-201. https://doi.org/10.1016/j.applthermaleng.2013.01.039

Bellia, L., Marino, C., Minichiello, F., & Pedace, A. (2014). An Overview on Solar Shading Systems for Buildings. *Energy Procedia*, ***62***, 309-317. https://doi.org/10.1016/j.egypro.2014.12.392

Brager, G., Borgeson, S., & Lee, Y. (2007). Summary Report: Control Strategies for Mixed-Mode Buildings. Center for the Built Environment (CBE). Retrieved 10th March, 2023 from https://escholarship.org/content/qt8kp8352h/qt8kp8352hnoSplash_04eb99f455f676cb42056bd1bacaf10c.pdf

Calama-González, C. M., Suárez, R., & León-Rodríguez, Á. L. (2018). Thermal and Lighting Consumption Savings in Classrooms Retrofitted with Shading Devices in a Hot Climate. *Energies*, ***11***(10), 2790. https://dx.doi.org/10.3390/en11102790

Calama-González, C. M., Suárez, R., León-Rodríguez, Á. L., & Ferrari, S. (2019). Assessment of Indoor Environmental Quality for Retrofitting Classrooms with An Egg-Crate Shading Device in A Hot Climate. *SUSTAINABILITY*, ***11***(4), 1078. https://dx.doi.org/10.3390/su11041078

Dubois, M.-C. (1997). *Solar shading and building energy use*. Lund University, Sweden. Retrieved 25th January, 2023 from https://www.bkl.lth.se/fileadmin/byggnadskonstruktion/publications/TABK-3000/Report3049.pdf

Evangelisti, L., Guattari, C., Asdrubali, F., & de Lieto Vollaro, R. (2020). An experimental investigation of the thermal performance of a building solar shading device. *Journal of Building Engineering*, ***28***, 101089. https://doi.org/10.1016/j.jobe.2019.101089

Girei, M., Dodo, Y., Yahaya Abdul, A., & Mu'azu, J. (2021). Effectiveness of Shading Devices for Solar Protection in Hot Climates: a Case Study of MAUTECH Yola, Nigeria. *International Journal of Energy and Environmental Engineering*, ***1***(2), 77-80. *https://www.researchgate.net/publication/35332709_EFFECTIVENESS_OF_SHADING_DEVICES_FOR_SOLAR_PROTECTION_IN_HOT_CLIMATES_A_CASE_STUDY_OF_MAUTECH_YOLA_NIGERIA*

Guevara, G., Soriano, G., & Mino-Rodriguez, I. (2021). Thermal comfort in university classrooms: An experimental study in the tropics. *Building and Environment*, ***187***, 107430. https://doi.org/10.1016/j.buildenv.2020.107430

Harris, A. (2018). Sun Intensity vs. Angle. Sciencing by Leaf Group. Retrieved 12th March, 2023 from https://sciencing.com/sun-intensity-vs-angle-23529.html

Ho, M.-C., Chiang, C.-M., Chou, P.-C., Chang, K.-F., & Lee, C.-Y. (2008). Optimal sun-shading design for enhanced daylight illumination of subtropical classrooms. *Energy and Buildings*, ***40***(10), 1844-1855. https://doi.org/10.1016/j.enbuild.2008.04.012

Ibhadode, O., Okougha, F., Nwafor, C., & Essang, N. (2017). An experimental-study on ventilation of public schools in Akure, Oshogbo and Ado-ekiti cities in South-western Nigeria. *IOSR Journal of Mechanical and Civil Engineering*, ***14***(5), 34-43. https://www.iosrjournals.org/iosr-jmce/pages/14(5)Version-1.html

Ishaq, M., & Alibaba, H. (2017). Effects of Shading Device on Thermal Comfort of Residential Building in Northern Nigeria. *International Journal of Scientific and Engineering Research*, ***8***(12), 1021-1029. https://www.ijser.org/researchpaper/Effects-Of-Shading-Device-On-Thermal-Comfort-Of-Residential-Building-In-Northern-Nigeria.pdf

Jegede, O. E., & Taki, A. (2021). Optimization of building envelopes using indigenous materials to achieve thermal comfort and affordable housing in Abuja, Nigeria. *International Journal of Building Pathology and Adaptation*, ***40***(2), 219-247. https://doi.org/10.1108/IJBPA-01-2021-0009

Kamal, M. A. (2010). A study on shading of buildings as a preventive measure for passive cooling and energy conservation in buildings. *International Journal of Civil & Environmental Engineering*, ***10***(6), 19-22. http://ijens.org/102406-5252%20IJCEE-IJENS.pdf

Kamal, M. A. (2013). Le Corbusier's solar shading strategy for tropical environment: A sustainable approach. *Journal of Architectural/Planning Research and Studies (JARS)*, ***10***(1), 19-26. https://so02.tci-thaijo.org/index.php/jars/article/view/12915

Lee, K. S., Han, K. J., & Lee, J. W. (2017). The Impact of Shading Type and Azimuth Orientation on the Daylighting in a Classroom–Focusing on Effectiveness of Façade Shading, Comparing the Results of DA and UDI. *Energies*, ***10***(5), 635. https://doi.org/10.3390/en10050635

Littlefair, P. (2018). Solar Shading of Buildings. IHS Markit. Retrieved 30th December 2022 from https://www.brebookshop.com/samples/327971.pdf

Mobolade, T., & Pourvahidi, P. (2020). Bioclimatic Approach for Climate Classification of Nigeria. *SUSTAINABILITY*, ***12***(10), 4192. https://doi.org/10.3390/su12104192

Nikolaou, G. I., & Meresi, A. K. (2021). Shading and daylighting strategies in classrooms: a comparative study in the four climate zones in Greece using Daylight Factor values. *IOP Conference Series: Earth and Environmental Science*, ***899***(1), 012036. https://doi.org/10.1088/1755-1315/899/1/012036

Ogbonna, A. C., & Harris, D. J. (2008). Thermal comfort in sub-Saharan Africa: Field study report in Jos-Nigeria. *Applied Energy*, ***85***(1), 1-11. https://doi.org/10.1016/j.apenergy.2007.06.005

Porras-Salazar, J. A., Wyon, D. P., Piderit-Moreno, B., Contreras-Espinoza, S., & Wargocki, P. (2018). Reducing classroom temperature in a tropical climate improved the thermal comfort and the performance of elementary school pupils. *Indoor Air*, ***28***(6), 892-904. https://doi.org/10.1111/ina.12501

Prowler, D. (2016). *Sun Control and Shading Devices. Whole Building Design Guide*. Retrieved 12th March, 2023 from https://www.wbdg.org/resources/sun-control-and-shading-devices

Shahdan, M., Ahmad, S., & Hussin, M. (2018). External shading devices for energy efficient building. *IOP Conference Series: Earth and Environmental Science,*

Siti Handjarinto, & Veronica I, S. (1998). Thermal Comfort Study in a Naturally Ventilated Residential Building in a Tropical Hot-Humid Climate Region [Conference Proceedings]. *Symposium on Improving Building Systems in Hot and Humid Climate,* Fort Worth, Texas, United States. https://core.ac.uk/works/39526217

Sok-Paupardin, E. (2021). *Daylight Glare: How Does it Affect Health, Well-being and Performance? SageGlass.* Retrieved 14th February 2023 from https://www.sageglass.com/industry-insights/daylight-glare-how-does-it-affect-health-well-being-and-performance

Song, B., Bai, L., & Yang, L. (2022). Analysis of the long-term effects of solar radiation on the indoor thermal comfort in office buildings. *Energy*, ***247***, 123499. https://doi.org/10.1016/j.energy.2022.123499

Soufiane, F., Ahriz, A., Mohamed, M., & Salaheddine, D. (2019). Quantifying the effectiveness of mass proportions and the orientation for buildings on thermal performance in Tebessa, Algeria. *IOP Conference Series Earth and Environmental Science*, ***397***, 012008. https://doi.org/10.1088/1755-1315/397/1/012008

Transparency. (2020). *Nigeria's Climate Action and Responses to the Covid-19 Crisis. Climate Transparency*. Retrieved 6th July, 2022 from https://www.climate-transparency.org/wp-content/uploads/2021/01/Nigeria-CT-2020.pdf

ürge-Vorsatz, D., Danny Harvey, L. D., Mirasgedis, S., & Levine, M. D. (2007). Mitigating CO2 emissions from energy use in the world's buildings. *Building Research & Information*, ***35***(4), 379-398. https://doi.org/10.1080/09613210701325883

Viula, R. (2022). Discomfort glare from daylight in classrooms [PhD Thesis, TuDelft University of Technology]. Netherland. https://doi.org/10.7480/abe.2022.14

Wah, L. Y., Ahmad, M. H., & Ossen, D. R. (2008). Review on measuring tools for energy efficient solar shading strategies in tropical climate. *Jurnal Alam Bina*, ***14***(5), 33-42. http://eprints.utm.my/id/eprint/9939/

Wavomba, Z. (2019). *How Latitude & Altitude Affect Temperature*. Sciencing by Leaf Group. Retrieved 12th March, 2023 from https://sciencing.com/info-8686864-latitude-altitude-affect-temperature.html

Yener, A. K. (2002). Daylight Analysis in Classrooms with Solar Control. *Architectural Science Review*, ***45***(4), 311-316. https://doi.org/10.1080/00038628.2002.9696946