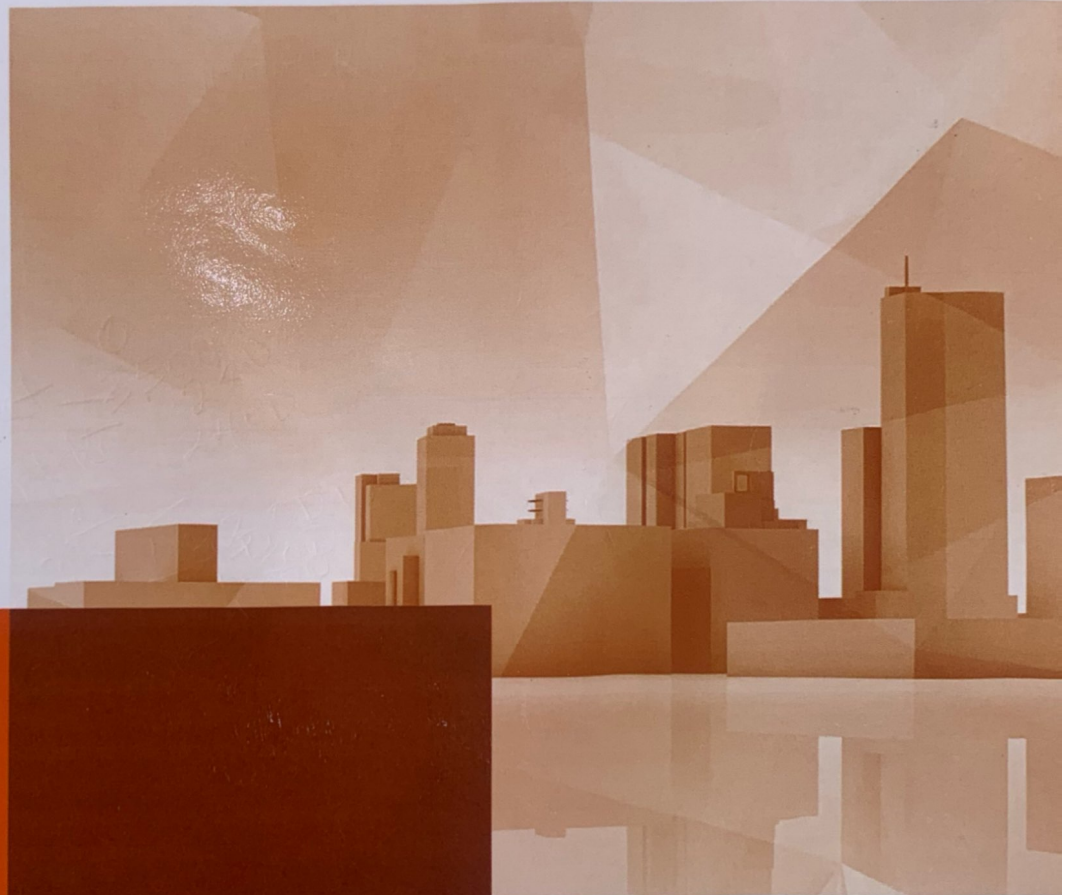


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Impact of Building Orientation on the Indoor Thermal Comfort of Tropical Residential Design in Ogbomoso, Nigeria

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Abstract

This study optimized building orientation angle for reduced solar gains into the interiors, with a view to reducing required annual cooling loads for energy efficient building operation. The research focus was directed at the residential building design in the tropical city of Ogbomoso, Nigeria. Through building simulation (using *DesignBuilder* software), four virtual models of a three-bedroom twin-apartments residential building were generated. Each model was orientated in an easily definable alternate angle of 45°, beginning with the East-West orientation (i.e. along 0° angular direction, taking the Eastward direction as 0°) tagged *E-W-Building*, North-East/South-West (45°) tagged *NE-SW-Building*, North-South (90°) tagged *Northward-Building*, and; South-East/North-West (135°) tagged *NW-SE-Building*. Thus, a total of four (4) test scenarios/models were created. These models were subjected individually to a 12-month energy performance simulation, to evaluate their indoor comfort levels in terms of the indoor solar gains through the exterior windows as well as the required corresponding cooling loads (to offset the discomfort likely to be experienced by the occupants). These variables were considered with regard to their daily, monthly and annual values. Results of the simulation show that the model performances are in the best order of *E-W-Building*, *NW-SE-Building*, *NE-SW-Building* and *Northward-Building*, oriented with their individual longer side along the direction of the *East-West*, *North-West/South-East*, *North-East/South-West*, and *North-South* axes, respectively. Specifically, an annual 8% reduction in the indoor solar gains, and 23% decrease in the annual cooling thermal loads were recorded by the *East-West* oriented building (*E-W-Building*), relative to the *North-South* oriented one (*Northward-Building*). It could be inferred from the simulation outputs therefore, that the building orientation elongated along the East-West axis is the most suitable for minimised indoor solar gains as it allows maximisation of the North and South-facing façades (easily protected with small overhangs), and minimisation of the East and West-facing ones (that are rather difficult to protect). This in effect, minimises the heat gains into the building with corresponding reduced cooling loads, for improved attainment of indoor thermal comfort. The outcome of this study demonstrates minimized building overall energy demand with a view to reducing carbon emissions, for sustainable healthy, safe and comfortable global environment.

Keywords: Building Orientation, Cooling loads, Energy, Simulation, Solar gains, Thermal Comfort, Tropics,

Introduction

Buildings constitute large consumers of energy in built environment, especially in regions with extreme climatic conditions (Latha, Darshana and Venugopal, 2015). In particular, building sector accounts for about 39% of World CO₂-equivalent emissions. It is also responsible for over 30% of global energy consumption, 50% of extraction of raw materials and about one-third of drinking water consumption (Ascione, Bianco, Iovane, Mastellone, and Mauro, 2021; Attoye and Hassan, 2017;

Lotfabadi, Alibaba and Arfaei, 2016; Nejat, 2015). With the fast growth in population, economic activities and rapid urbanization, particularly in developing countries, global building stock is projected to increase over time due to new constructions. This is expected to double by 2060 (Lotfabadi, 2013). In tropical countries especially, building sector constitutes a major energy consumer (Prianto and Depecker, 2002). Thus, the need for suitable initiatives, relevant policies and action plans to moderate energy demand in the construction

sector, to minimize potential undesirable consequent impact on the local and global warming which may otherwise be unpleasant for human general wellbeing, could not be overemphasized (Attoye & Hassan, 2017; Jiang, Liu and Liu, 2016; Camanzi, Alikadic, Compagnoni and Merloni, 2017).

Sunny climate, especially the tropical region, presents an excess of solar gains that cause high energy consumption due to the interior cooling needs, and thus, the need for proper management of sunlight impinging onto building facades for energy-efficient building design and operation (Olaniyan, Onigbogi, and Sulaiman, 2023; González-Pardo, Rodríguez, González-Aguilar, & Romero, 2014). Tropical region is known for its elevated outdoor temperature, relative humidity, and solar radiation with its attendant influence on the indoor energy performance of buildings (Kirimtat, Koyunbaba, Chatzikonstantinou, & Sariyildiz, 2016; Kirimtat, Krejcar, Ekici, & Tasgetiren, 2019). These conditions have significant influence on the indoor energy performance of buildings, and consequently, negative impacts on the indoor thermal comfort of the occupants. To address the situation, mechanical devices inclusive of air conditioners, fans and various kinds of ventilation devices that are energy intensive, operational with only electricity, and costly to maintain are installed (Latha, Darshana and Venugopal, 2015). In most situations, these mechanical cooling devices remain non-functional, incapable of offering thermal comfort, without energy input, and do offer solutions that are neither

environmentally friendly nor energy sustainable. Hence, exploration of alternative and more sustainable passive approach to address the challenge may offer the required sustainable solution for thermal comfort demands (Kirimtat, Krejcar, Ekici, and Fatih, 2019; Karyono, 2017).

Sequel to the above, consideration of the building orientation in the building design process is one of such sustainable passive approaches as the design process plays an important role in developing sustainable buildings. Building by itself can contribute to thermal discomfort and attention must be given to its orientation for proper application at the design and construction stages. It therefore requires proper evaluation and useful integration of relevant environmental elements into the building design (Kirimtat et al., 2016; Wall and Poirazis, 2008; Hien et al., 2005). Building orientation is very critical in tropical climates and the basic rule is to minimise façades facing the East and West due to the low position of the sun in the morning and afternoon respectively. This is because East and west-facing façades are harder to protect from solar insolation than those facing North and South (UN-Habitat, 2014). One factor increasing the cooling energy demands is the impact of direct and diffuse solar radiations on building, which is a consequence of the changing positions of the Sun along the sun path as illustrated in Figure 1, with the effect of raising the indoor surface, air temperatures, the basis of the seasons, among others (Dai et al, 2023; Valladares-Rendón, Schmid and Lo, 2017).

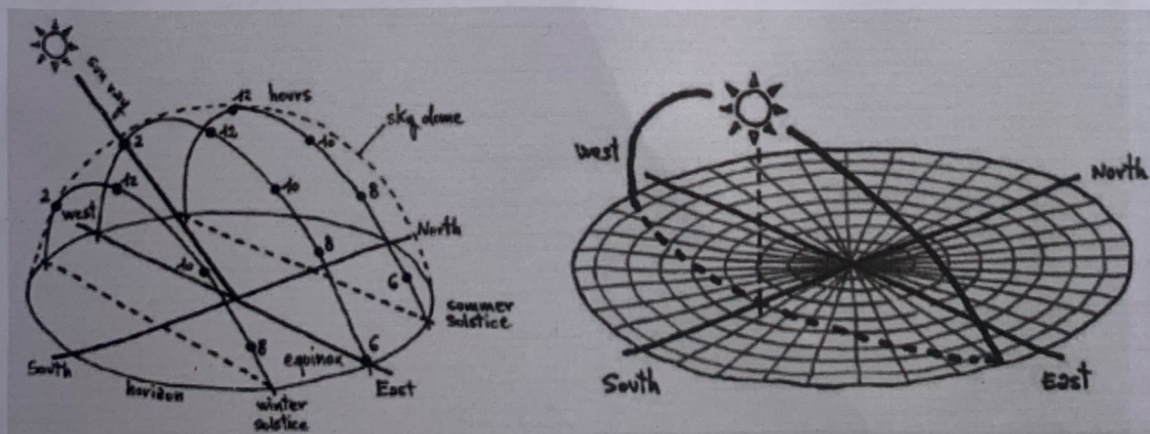


Figure 1: Changing Positions of the sun as it traverses from the East to the West
(Source: UN-Habitat, 2014)

Thus, application of solar geometry is very important for architectural design and energy efficient strategies, since solar energy greatly influences the energy performance of buildings. When the Sun is low on the horizon, it is more difficult to control its effect and the rays can penetrate deeply through the windows leading to its indoor discomfort, arising from the solar insolation. It should be noted that in tropical and equatorial regions, the Sun has an altitude higher than 30° for about 75% of the year. However, the high solar altitude makes the south or north facades, on which more inclined rays fall in the central part of the day, less critical than the East and West ones during morning and evening, when the Sun is low and can penetrate more deeply into the buildings (UN-Habitat, 2014). Thus, the aim of this study is to investigate the impact that building orientation has on the cooling energy needs in a small-scale tropical residential building design with a view to establishing an acceptable orientation for optimum energy performance in a residential building design for Ogbomoso, Nigeria. This is to improve on the energy efficiency of the building, and reduce carbon footprint of building stock worldwide, thereby aligning with the Sustainable Development Goal-2030 of the United Nations (Olaniyan, 2023).

Methodology

The study area, Ogbomoso, Nigeria, is situated within the derived savannah region, and serves as a gateway to the Northern part of Nigeria, from the South. It exists within the transition zone of rainforest and the savannah as it lies on $8^\circ 10'$ North of the equator and $4^\circ 15'$ East of Greenwich Meridian. Referencing Köppen-Geiger climate classification, the study area is classified 'Aw' climate having tropical wet and dry climates with the highest and lowest number of rainy days in July (24.70 days) and December (0.73 days) respectively. It has mean annual rainfall of about 1200mm, and experiences over $10\text{KJ}/\text{m}^2/\text{day}$ of radiation for some months, which corresponds to an average of 76.53 hours of sunshine per month, and 2323.51 hours annually (En.climate, 2022; Olaniyan, 2012). This explains the basis of the indoor thermal discomfort often experienced in most part of the year in the study area. Hence, the need for appropriate design intervention for sustainable indoor thermal experience by the occupants.

This research studied the impact of building orientation on the indoor thermal environment in a tropical residential design. To analyze building's energy performance, building energy simulation is

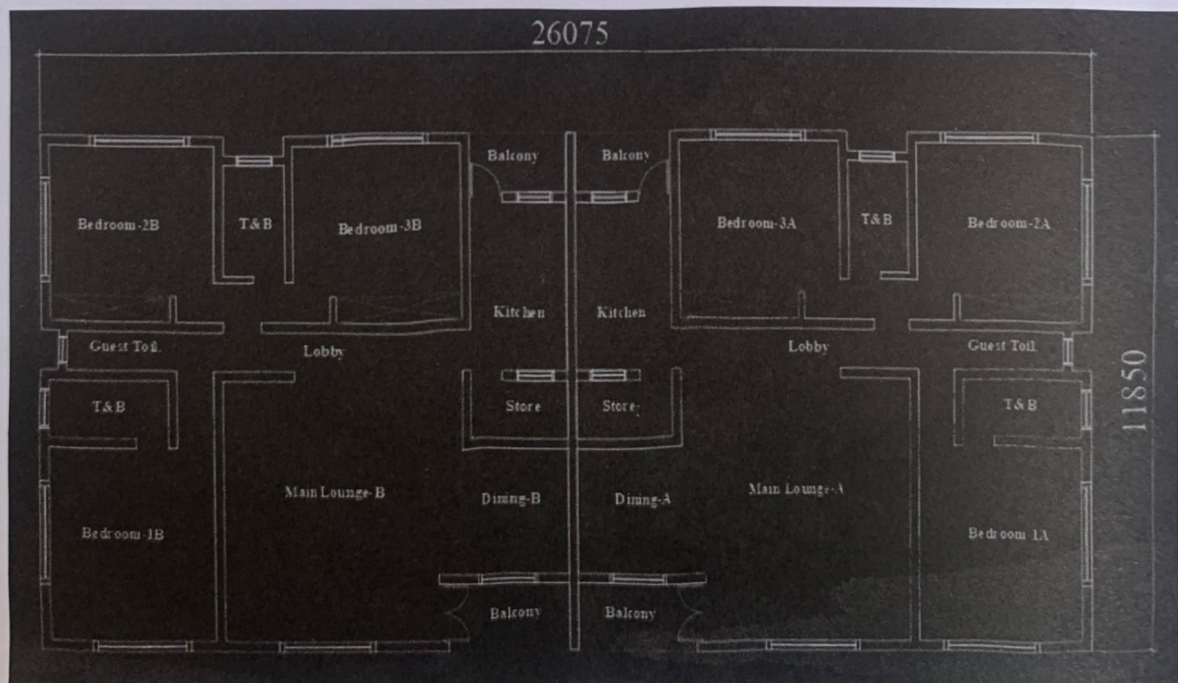


Figure 2: Floor Plan of the Virtual Building Model

often adopted as the best approach within the building industry (Olaniyan, Onigbogi & Sulaiman, 2023; Clarke, 2001). It is widely used to predict the future indoor climate of the proposed buildings and estimate the energy performance of completed buildings. Thus, for the purpose of investigating the improvements in cooling loads as a result of varied building orientation in this context, thermal performance simulations were carried out using *DesignBuilder*, a software with established capabilities for energy assessment. It has been uniquely developed to run complete EnergyPlus simulations on building models within the same interface, and has been used by several researchers to conduct building thermal performance research with successful and reliable outcomes in previous studies (DesignBuilder, 2023; Abdullah et al, 2022; Olaniyan, Ayinla and Odetoye, 2013). It is an hourly energy simulation engine for modelling building's heating, cooling, lighting, ventilating and other energy flows. For ease of result analyses, these simulations were run for the whole year (i.e., 12 months) and the outputs were obtained in forms of hourly, daily, monthly and annual data.

Virtual model of a three-bedroom twin-apartments building (as predominantly observed in the study area) occupying a total area of 255.75 square metre, was generated and subjected to energy performance simulation analysis for this study. This is illustrated in Figure 2 (i.e., the Floor Plan) as the three-dimensional model of the building (obtained on the *DesignBuilder* interface) is shown in Figure 3. As obtainable in the study area, the building wall is made of 225mm hollow sandcrete block, finished with 12mm thick sand-cement mortar on both internal and external surfaces. The window is of 6mm thick clear glass, and the building is complemented with 40mm thick wooden panel doors. The roof is of 0.45mm thick long span aluminium sheet on timber roof carcass, finished underneath with 6mm thick Asbestos ceiling sheets. In line with this research focus, to study the impact of building orientation on the indoor thermal environment, different building orientations (of the same building model) were established, beginning with the East-West orientation (i.e. along 0° angular direction, taking the Eastward direction as 0°) tagged *E-W-Building*, and subsequently rotated at 45° increment in an

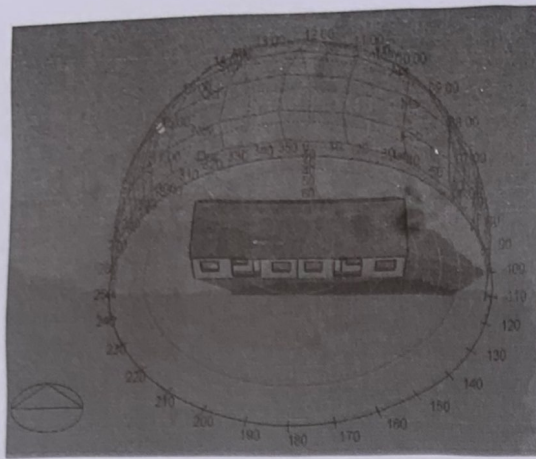
anticlockwise direction (Refer to Figure 4) through three other directions of: North-East/South-West, tagged *NE-SW-Building*, North-South tagged *Northward-Building*, and South-East/North-West tagged *NW-SE-Building*, to create a total of four (4) test scenarios. The image as displayed for each model (Figure 3) represents the presumed outlook taken in a typical tropical equinox day (i.e., 21 June) at 4pm. These models were subjected individually to a 12-month thermal simulation, to evaluate their indoor comfort levels in terms of the indoor *solar gains through the exterior windows* as well as the required corresponding *cooling loads* (to offset the discomfort likely to be experienced by the occupants). These variables were considered with regard to their daily, monthly and annual values.

Results Presentation, Discussion and Implications

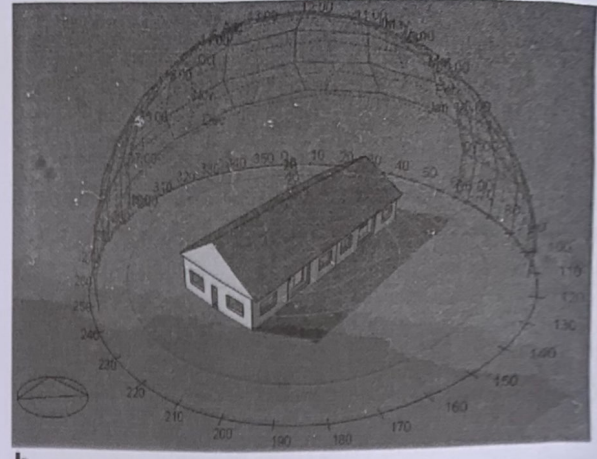
(I). Prevalent Outdoor Weather Conditions Vis-à-vis Building Indoor Thermal Experience in the Study Area

The study area, Ogbomoso, Nigeria, is a typical tropical city characterised by elevated thermal conditions as reflected in the simulation outputs. Details of the monthly *Solar Radiation* (considering both *direct* and *diffuse*) and *Outside Dry Bulb Temperature* are presented in Figure 5. These simulation outputs are important as they form the basis for the indoor solar gains, the consequence of which may result in indoor thermal discomfort as often experienced by the occupants.

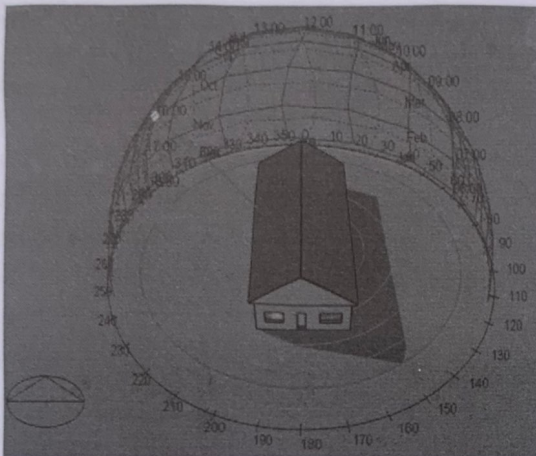
From Figure 5, the climatic data for the study area indicate high solar radiations particularly, between October and May, with each month experiencing almost 100 KWh/m² area of Diffuse Radiation. The month of March recorded the highest value of 114.13 KWh/m². This is also applicable to the Direct Radiation over the same period, with the highest value of 84.45 KWh/m² recorded in March. Outside Dry Bulb Temperature ranges between 24.8 °C (in August) and 28.6 °C (in April) over the same period. These outdoor thermal situations are usually determined by the position and path of the Sun in the sky, characterized by the changing azimuth and altitude angles throughout a day at the geographical location of the study area (Pal and Das, 2015). Through the walling fabrics, windows, roof, among



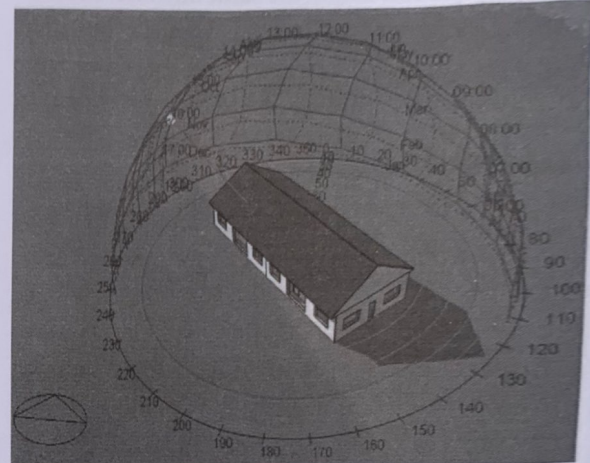
a



b



c



d

Figure 3: Typical outlooks of the Building Virtual models vis-à-vis their orientations on DesignBuilder simulation interface: (a) *E-W-Building Orientation @ 0°*; (b) *NE-SW-Building Orientation @ 45°*; (c) *Northward-Building Orientation @ 90°*; and; (d) *NW-SE-Building Orientation @ 135°*

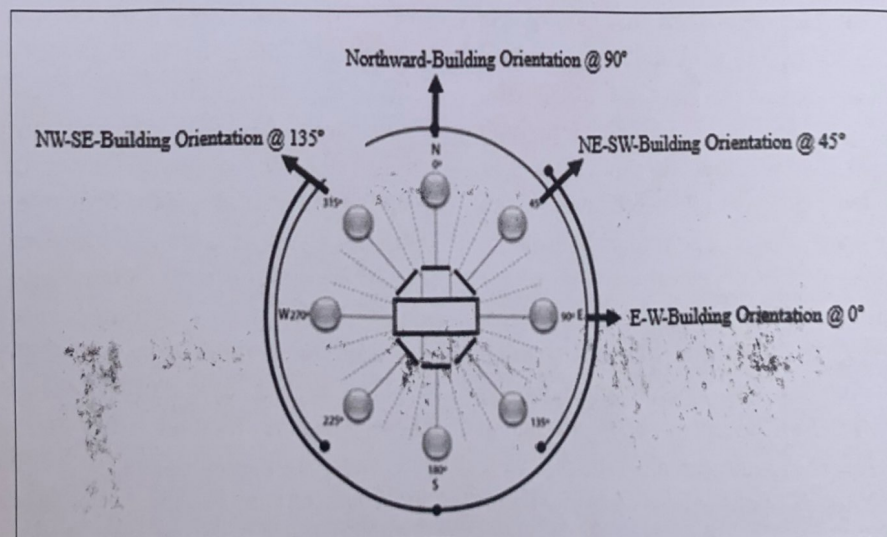


Figure 4: Illustrative Orientation of the Building Model in four Angular Directions at 45° anticlockwise increment (Source: Modified image originally adopted from Valladares-Rendón, Schmid and Lo, 2017)

others, these radiations form the basis for the indoor solar gains from which indoor thermal discomfort is experienced. These often necessitate the need for additional efforts to improve the thermal conditions of the interiors, in the study area.

(ii). Thermal Impacts of Varying Building Orientations Vis-à-vis Changing Sun Path on the Indoor Thermal Comfort of Tropical Residential Design

Attainment of indoor thermal comfort in the tropical design is largely influenced by the amount of solar penetration. As revealed in the previous section, the study area is characterised by high solar radiations with varying radiation values due to the changing Sun's azimuth and altitude angles through different hours of the day. Thus, varying orientations of the building model (as described in the methodology) define the actual amount of the solar gains into each building as revealed in the daily simulation outputs shown in Figure 6.

Considering Figure 6, high solar gains are observed in *NW-SE-Building* and *Northward-Building* between the hours of 900 and 1030, due to their orientations that exposed larger surface areas of the buildings (individually) to the early morning solar radiations (emanating from the just rising Sun in the East). This is contrary to the two other orientations of the *E-W-*

Building and more importantly, *NE-SW-Building* with larger surface areas shielded away from the early morning solar radiations. As the Sun changes its position to reach its zenith around mid-day and thereabout in the afternoon (i.e., between the hours of 1200 and 1330), the solar gains into the *NW-SE-Building* and *Northward-Building* reduce, to reflect the changing Sun's azimuth and altitude angles.

Conversely, as the Sun traverses its path towards the West and due to the high solar gains in the evening period (i.e., between the hours of 1530 and 1700) emanating from the Sun setting in the West, *NE-SW-Building* experienced highest solar radiation as the *NW-SE-Building* received the least. Arising from the foregoing, the cumulative effects of the solar gains into the buildings on monthly bases due to their varying orientations is shown in Figure 7.

On the average, it could be seen that the *Northward-Building* received highest solar gains due to the significant building surface areas (in view of its orientation) exposed to the Sun on its path. These monthly solar gains are further conflated into annual gains as reflected in Figure 8.

From Figure 8, *Northward-Building* which is oriented with its longer side along the North-South axis, thereby exposing more of its surface areas directly to the Eastern and Western directions is established with highest annual indoor solar gains of 34,097.09

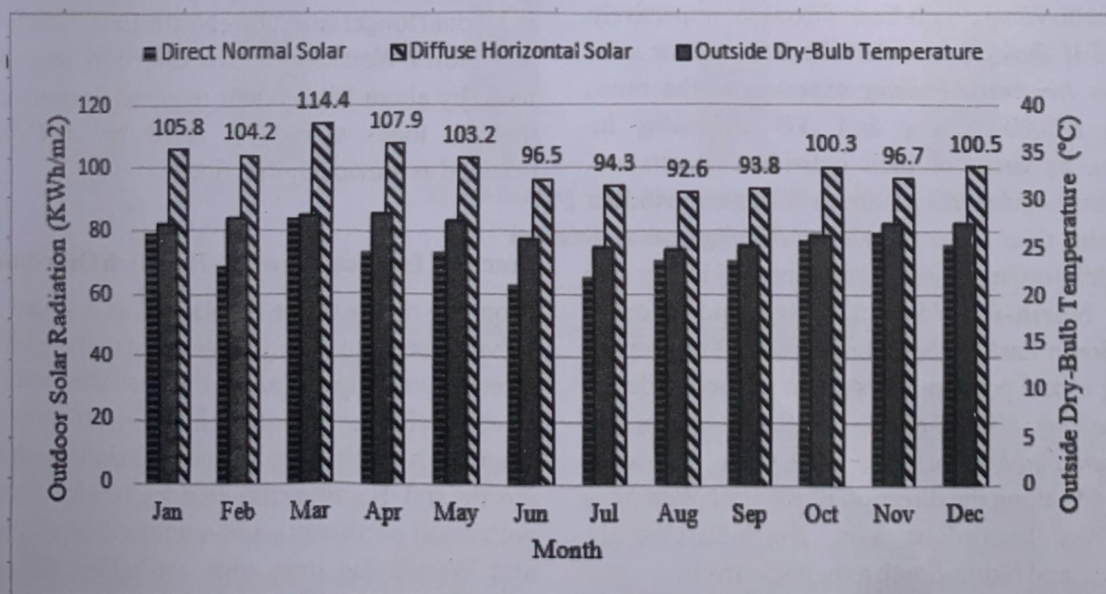


Figure 5: Simulation Output showing Solar Radiations (involving both direct and diffuse) and Outside Dry Bulb Temperature of the Study Area

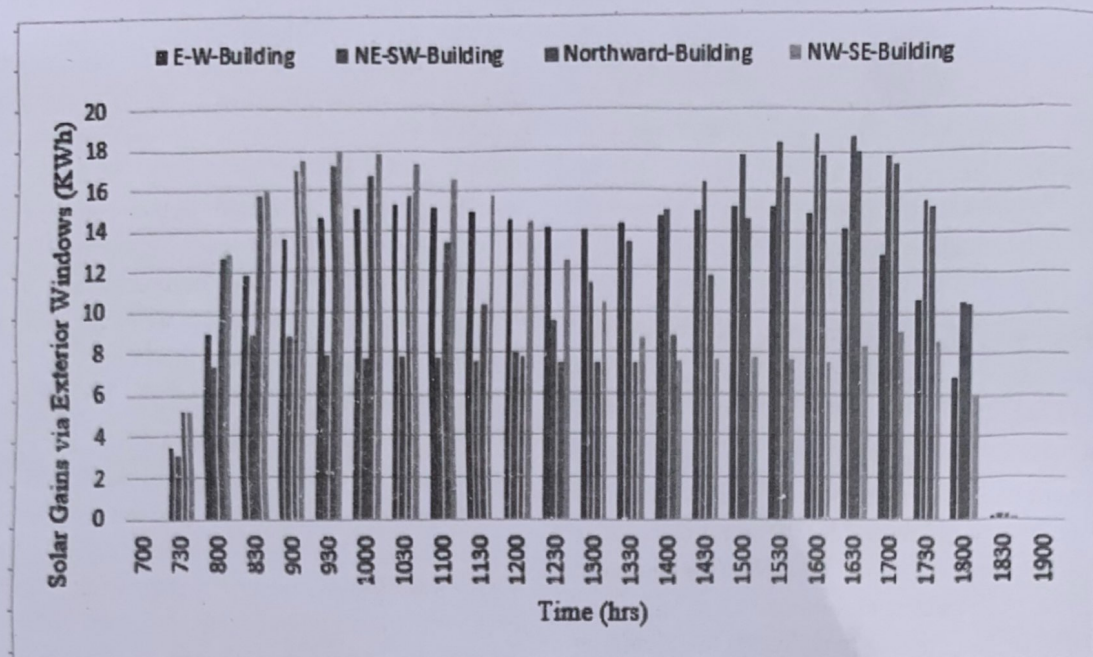


Figure 6: Daily Simulation Outputs showing *Solar Gains through the Exterior Windows* into each of the Building Models as captured on a Typical *June the 21st*

KWh relative to 28,991.08 KWh of the *E-W-Building* which is oriented with its longer side along the *East-West* axis, exposing more of its surface areas directly to the Northern and Southern directions. This is about 8.1% difference in the radiation values recorded by the two models, thereby putting *E-W-Building* at a better position. Similarly, *E-W-Building* is about 5% lower in the solar radiation gains than either of *NE-SW-Building* and *NW-SE-Building* oriented with their longer side along North-East/South-West, and North-West/South-East direction respectively. Thus, *E-W-Building* recorded the least indoor solar gains as *Northward-Building* experienced the most, leaving *NE-SW-Building* and *NW-SE-Building* in-between, by virtue of their individual orientation. Also, *Northward-Building* is about 5% higher in indoor solar gains than either of *NE-SW-Building* and *NW-SE-Building* oriented with their individual longer side along North-East/South-West, and North-West/South-East direction respectively. This implies that the model performances are in the best order of *E-W-Building*, *NW-SE-Building*, *NE-SW-Building* and *Northward-Building*, oriented with their individual longer side along the direction of the East-West axis, North-West/South-East axis, North-East/South-West axis, and North-South axis, respectively.

As a direct consequence of the monthly and annual indoor solar gains as illustrated in Figures 7 and 8,

corresponding cooling loads, necessary to offset the thermal discomfort emanating from the solar gains are illustrated in Figures 9 and 10.

From Figures 9 and 10, it could be inferred that *E-W-Building* which is oriented with its longer side along the East-West axis would save about 23% of cooling thermal loads annually, relative to *Northward-Building* oriented with its longer side along the North-South axis. The trend is also applicable to both *NE-SW-Building* and *NW-SE-Building* oriented with their individual longer side along North-East/South-West, and North-West/South-East direction respectively, whereby about 8% of their required annual cooling thermal loads would be saved by *E-W-Building* oriented as previously described.

Practical Implication of the Research Outcome

From the results of the simulations as revealed in the previous sections, it can be observed that the building orientation elongated along the East-West axis is the most suitable for minimised indoor solar gains in the tropics. This is because it allows maximisation of the North and South-facing façades (easily protected with small overhangs), and minimisation of the East and West-facing ones (that are rather difficult to protect), thereby reducing the overall heat gains to the minimum. This finding aligns with the position of

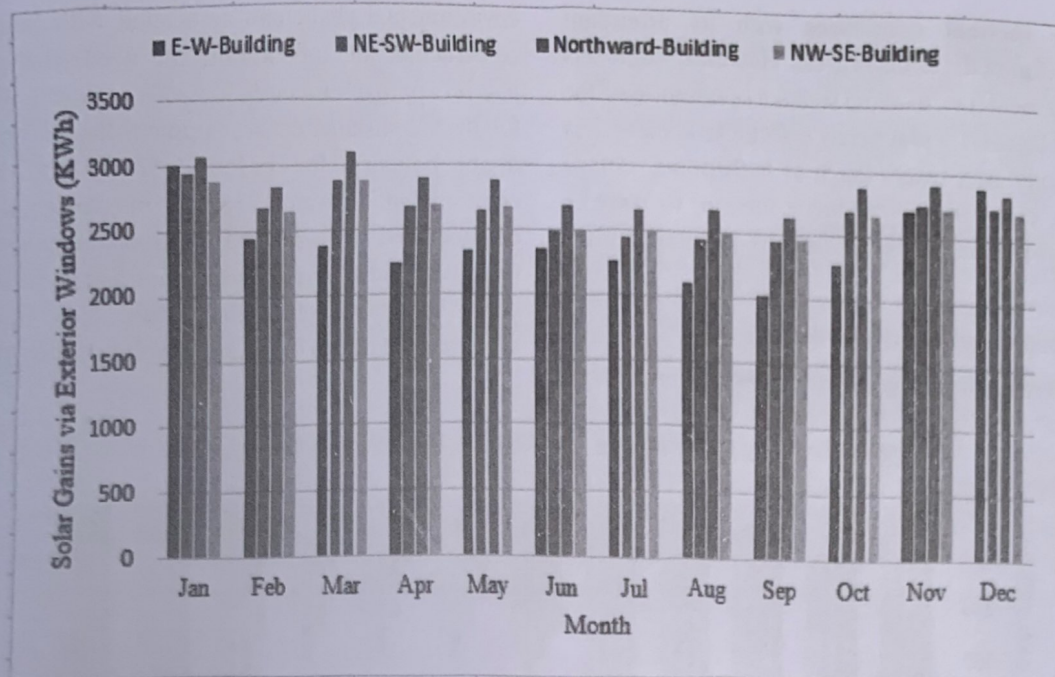


Figure 7: Monthly Simulation Outputs showing *Solar Gains through the Exterior Windows* into each of the Building Models

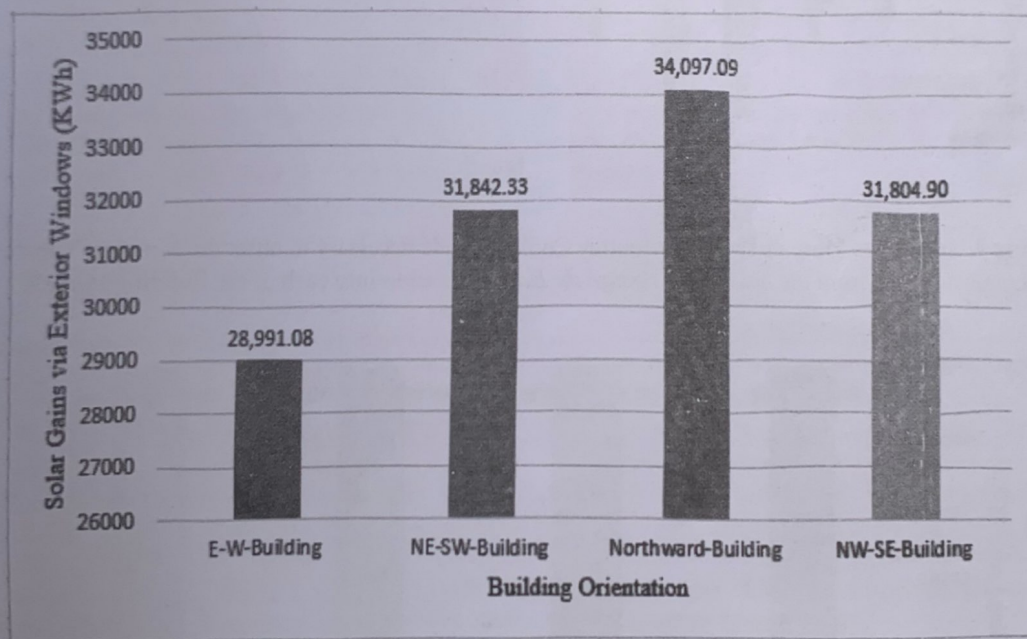


Figure 8: Annual Simulation Outputs showing *Solar Gains through the Exterior Windows* into each of the Building Models

Dai, Wang, Bart & Gao (2023), Olaniyan, Onigbogi and Sulaiman (2023), Alkali et al (2021), Carlander et al (2020), Adaji et al (2019), Ashmawy and Azmy, (2018), Srhayri and Bah, (2018), Vasov, Stevanovic, Bogdanovic, Ignjatovic & Randjelovic, (2018) and Adunola (2014). Thus, conscious efforts should be made to avoid western orientation of the largest

façades, since both solar radiation and temperature reach their peak in the afternoon. Besides, façades facing the East and West experience more solar penetration and are difficult to protect from solar insolation than those facing the North and South, due to the low position of the sun in the morning and afternoon respectively. These directly increase the

indoor thermal conditions with its attendant discomfort in the affected areas. However, where this arrangement (i.e., to avoid western orientation of the largest façades) is practically difficult to achieve, less frequently used spaces (such as bathrooms, storage rooms, etc.) can be introduced therein, to serve as effective thermal barrier within (UN-Habitat, 2014).

Conclusion and Recommendations

Considering the rising energy costs and increasing

environmental challenges associated with building construction and operations, the need to explore natural approach towards low energy consumption for overall sustainable development has become a major concern for practitioners in the built environment. Tropical region in particular, is characterized by elevated outdoor temperature, relative humidity, and solar radiation as it presents an excess of solar gains that cause high energy consumption due to the interior cooling needs. Thus,

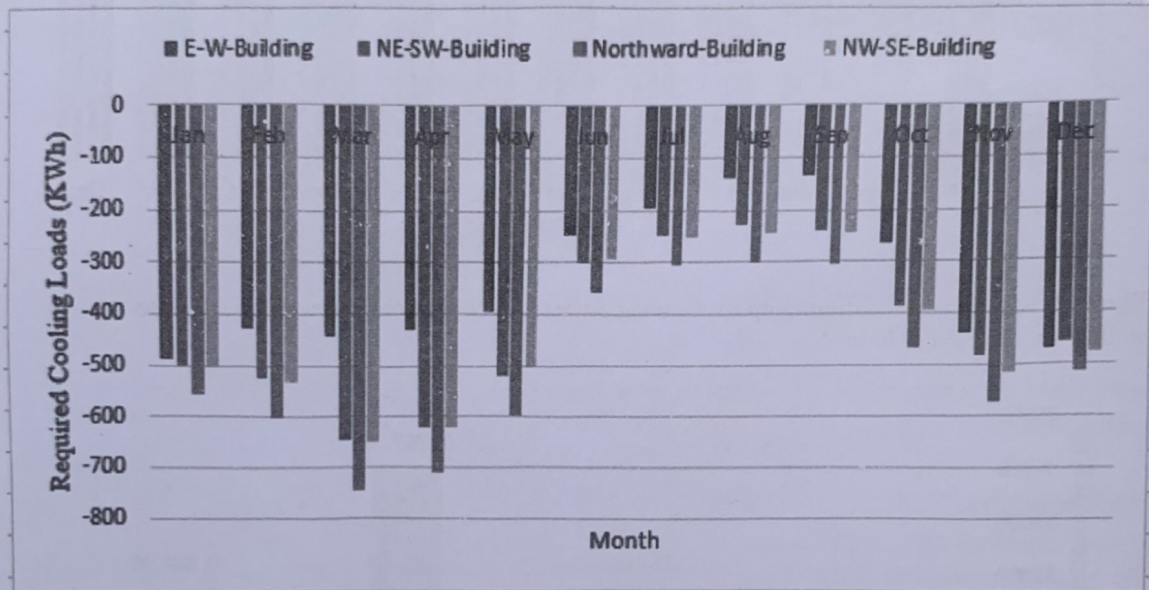


Figure 9: Simulation Outputs showing Monthly Cooling Loads necessary to offset the Monthly Thermal Discomfort arising from the *Solar Gains through the Exterior Windows* into each of the Building Models

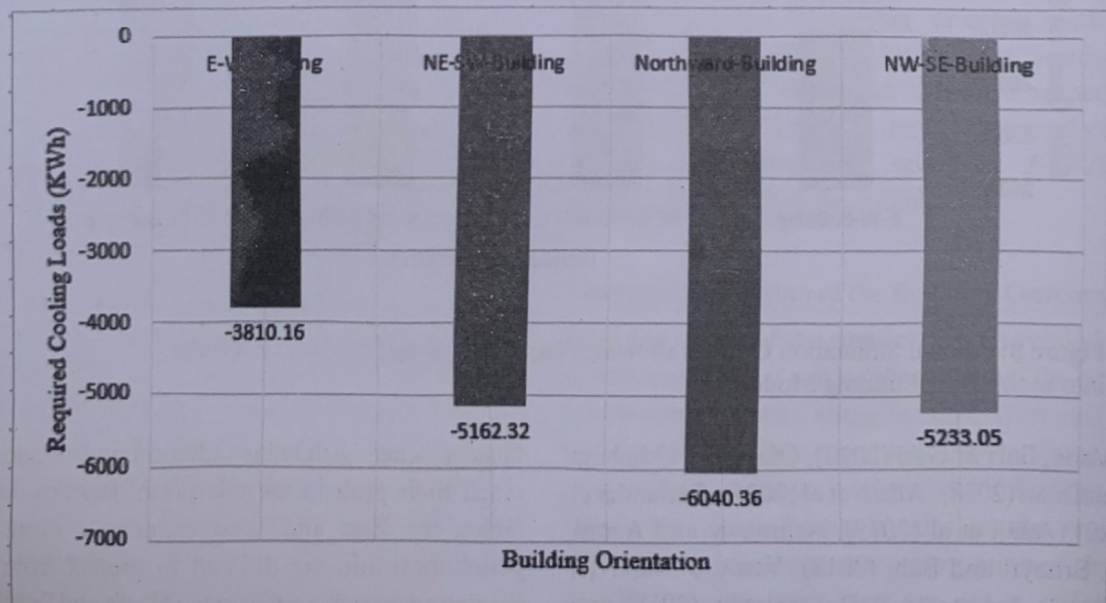


Figure 10: Simulation Outputs showing Annual Cooling Loads necessary to offset the Annual Thermal Discomfort arising from the *Solar Gains through the Exterior Windows* into each of the Building Models

understanding and proper management of sunrays impinging onto building facades is an important issue in the design of energy-efficient buildings. This is basically influenced by the orientation of significant building façade areas vis-à-vis the Sun path in its course of traversing from the East to the West on a daily basis. Through building energy performance simulation, this study therefore evaluated relevance of the interaction between the changing Sun positions relative to the building orientation, with a view to reducing indoor solar gains, for minimized cooling energy demands. This attempt is to facilitate control of the incoming sunrays, thereby reducing HVAC (Heating, Ventilating and Air-Conditioning) loads, decreasing the energy consumption and minimizing the energy costs. The results of the investigation

indicate potential reductions in the solar gains into the building interiors, subject to the varying angular orientations of the building particularly, residential apartments, as demonstrated within this context. This effort would substantially reduce the energy demand, minimize impact on the environment and decrease the carbon footprint of building stock at this micro-level in particular, and globally in general. It is therefore recommended that orientation of building should be elongated along the East-West axis for minimised indoor solar gains in the tropics. However, where this is practically impossible, less frequently used spaces (such as bathrooms, storage rooms, etc.) can be introduced, to serve as effective thermal barrier against the incoming solar heat-induced sunrays impinging on the receiving wall surfaces.

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