

Towards Sustainable Indoor Thermal Comfort in the Tropical Building Design: Comparative Performance Analysis of Fixed External Shading Elements and Differential Window Glass Thermal Properties

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Abstract: Tropical region is characterised by high outdoor solar radiation and temperature. These radiations penetrate into the interior particularly through the window glazing, thereby raising the indoor temperature with a resultant effect on high cooling energy demand (for comfortable indoor living condition). Of the identified three sustainable approaches towards inhibiting direct incoming indoor solar penetration in the tropical city of Ogbomoso, Nigeria, this study, through computer-based simulation technique, compared performance effectiveness of varying design interventions on the window composition/material adopted. Through multiple/iterative building performance simulation tool, *DesignBuilder*, the methodology involves virtual model of a three-bedroom residential building, typical of the prevailing building typology in the study area. This particular model served as the experimental *control model*. Three (3) variants of the *control model*, each with either externally mounted shading devices on the building envelope, or improved thermally resistant multilayer window glazing (i.e., double glazing) or low-emissivity coated window glazing material, were generated for individual performance effectiveness evaluation. All the four models were subjected to a twelve-month simulation cycle, to experience a year-round thermal conditions and evaluations individually. The results show that double-glazing window installation proved to be the most effective approach, with about 13.1 % improvement (i.e., solar radiation inhibition) on the indoor thermal gains. This is followed by the externally mounted shading devices (i.e., 11.1 % improvement) and the least inhibition (i.e., 5.0 %) was observed in the case of low-emissivity coated window glazing material. Adoption of double or more layers of glass panes in window fabrication for controlling indoor solar radiation penetration is therefore advised. Alternatively, integration of external window shading elements could be adopted. This study is directed towards reduction of cooling energy consumption in tropical buildings through efficient and sustainable indoor cooling mechanism capable of inhibiting solar gains into the building, with a focus on the performance roles and composition of windows in particular.

Keywords: Building Simulation, Solar Radiation, Sustainable Design, Thermal Comfort, Tropical Region.

I. Introduction

Tropical region is characterised by high solar radiation and outdoor temperature.

This situation accounts for the harsh outdoor weather conditions, marked with high temperature and relative humidity. These have significant influence on the indoor energy performance of a building, and consequently, negative impacts on the indoor thermal comfort of the occupants ([1], [2]). Within this region, sun is directly overhead at noon on June 21st (midsummer in the northern hemisphere) and December 21st (midsummer in the southern hemisphere) respectively ([2] - [4]). Thus, based

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on the direct sunlight incident on the building particularly the window areas, the accompanying incoming near-infrared energy (emanating from excessive direct sunlight) increases the temperature of the interior surfaces, leading to indoor thermal discomfort. This may otherwise necessitate the need for greater cooling requirements for the building occupants ([5]).

Building glazing units particularly windows, are necessary for provision of vision, daylighting, air ventilation and passive solar gain, among others. They also serve as physical and visual connection to outsiders ([6], [7]). However, glazing units are poor in thermal resistance compared with other building components as about one-third of the energy consumption through heat loss in a building, as well as large energy demand of cooling-dominated rooms in hot climates emanating from excessive heat gains are attributed to windows ([8], [9])). Window openings are therefore considered significant in the energy demand of buildings and the overall indoor thermal comfort. Thus, it is imperative to direct efforts towards reduction of energy consumption in buildings through efficient indoor cooling mechanism capable of inhibiting solar gains into the building, with a focus on the performance roles and composition of windows in particular. This is to be achieved without compromising required daylighting for necessary indoor visual comfort through the window.

Sequel to the above, various mechanisms to reduce indoor solar gains through direct incoming sunrays via windows have been examined by previous researchers. Impacts of shading devices mounted on the building envelopes to reduce overheating time of the building for improved indoor thermal conditions were demonstrated by several researchers inclusive of [10] - [20]). Shading

devices were placed either internally or externally or in-between the internal and external building spaces to inhibit solar radiation incident on the building particularly, windows. The devices were positioned to take the forms of dynamic facades, projections (chajja), cantilevers, louvres, fins, grating, light shelf, jaalis or even textiles. Use of plants as shading vegetation near the window was also introduced to provide shading effect, and reduce sunlight's direct radiation into the interior ([9], [17]). In all the cases, varying positive impacts of the device were observed. Alternatively, glazing units with improved thermal resistance performance through multilayer glazing and low emissivity coated glass surfaces ([1], [6], [7] [21 -23]), were examined. Considering the multilayered glazing, double or triple glazing with inert gas infill (like argon, krypton or xenon) between the glass panes was introduced. The gas acts as a stationary air layer to enhance thermal insulation performance of the window due to the low thermal conductivity of the gas, thereby decreasing the conduction heat transfer between the glass panes ([7], [9], [12], [13], [24] - [26]). This is premised on the fact that the heat transfer rate of a single-glazed window is about 2.5 times higher than that of a double-glazed window. Additionally, radiation energy accompanying the solar gains into the interior can be controlled by coating the glass surfaces with a low-emissivity material. In this case, sunlight transmission and reflection in different wavelengths can be controlled by changing the emissivity of the glass surface to reduce the heating impact on the interior [6], [12], [13], [27] [28]).

From the foregoing, this research therefore aims at comparing the performance efficiencies of the identified alternative sustainable approaches towards inhibiting solar radiation into the interior parts of the building (through

the window openings) for attainment of sustainable indoor thermal comfort. Within this context, the identified approaches include *adoption of Fixed External Shading Elements, introduction of double glazing for windows* as well as *coating of the window glass surfaces with a low-emissivity material*. The focus here is to arrive at a more efficient indoor cooling mechanism capable of inhibiting solar gains into the building, in the tropical city of Ogbomoso, Nigeria. This is to increase the energy efficiency of the building, reduce its running costs and minimize the overall environmental impacts [10], [29].

II. Materials and Methods

A. Study Area

The study area, Ogbomoso, is situated within the derived savannah region, as it occupies a geographical area that lies on 8° 10' North of the equator and 4° 15' East of Greenwich Meridian. It exists within the transition zone of rainforest and the savannah, and serves as a gateway to the Northern part of Nigeria from the South. In line with Köppen-Geiger climate classification, the climate is classified 'Aw' and has tropical wet and dry climates with the highest (24.70 days) and lowest (0.73 days) number of rainy days in July and December respectively ([30], [31]). It experiences its wet and dry seasons between April and October, as well as between November and March respectively. Between the extremes of the two seasons, it records precipitation variation of about 178 mm, with mean annual rainfall of about 1200mm. Months of January (42.54%) and September record highest (42.5%) and lowest (85.18%) values for Relative Humidity respectively. Being a tropical climate, the study area has over 10KJ/m²/day for some months, with an average of 76.53 hours and 2323.51 hours of sunshine per month and annually respectively ([30], [31]). This often results into interior thermal discomfort in most part of the year. Hence, the need for suitable and

sustainable thermal comfort-based design interventions in the area.

B. Methods

The study compares performance effectiveness of three identified sustainable approaches towards inhibiting solar radiation penetration into the interior parts of the building (through the window openings) with a view to attaining sustainable indoor thermal comfort. These approaches include adoption of Fixed External Shading Elements, introduction of double glazing for windows as well as coating of the window glass surfaces with a low-emissivity material. The research method was simulation-based, using a virtual model of a predominantly adopted building typology (design) in the study area. This involved adoption of multiple/iterative building performance simulation tool for comparative evaluation of indoor thermal performance of the building. As a modern design tool, numerical simulation allows ease of analysing the influence of design elements on indoor thermal comfort for sustainable building development [32], [33]). In view of the complex inter-relationships between climate, design characteristics, building occupants, electrical as well as mechanical systems in a building, it is established that simulation modeling is an effective means for estimating the energy performance of buildings ([29], [34]). Of the numerous available simulation tools, *DesignBuilder* software [35], an *EnergyPlus* integrated dynamic building energy simulation engine for modelling building heating, cooling, lighting, ventilating and other energy flows, which allows complete simulations within the same interface was adopted for the study. Using the specified construction components, the software models the conduction of heat through walls, windows, roofs, ground and other opaque parts of the building envelope.

Thus, virtual model of a typical floor plan for a three-bedroom apartment with an approach balcony (occupying a total area of 103.85 square metre), as predominant in the study area was generated. This is as illustrated on the DesignBuilder interface (Figures 1 & 2). In its composition, the blockwall which is of 3000 mm height, is made of 225 mm wide hollow Sandcrete block (i.e. 450 by 225 by 225 mm) with 12 mm thick sand-cement mortar on both internal and external surfaces. The roof which covers the whole building with 600 mm overhangs around the external walls, is constructed of 0.45mm thick long span aluminum sheet on timber roof carcass, finished underneath with 6mm thick Asbestos ceiling sheets. Aluminum sliding frames embedded with 6mm thick clear glass constitute the window components. Wooden door panels attached to wooden frames formed the door. For the purpose of the comparative evaluations, this particular building model, tagged *Control-Building*, serves as the control model while three variants of the model, each individually/separately with: attached shading elements only (as predominant in the study area); double glazing windows only, and; low-emissivity window coatings, were generated and labelled ***Shaded-Building***, ***Double-G-Building***, and ***Low-E-Building*** respectively. Details of the Thermo-physical Properties of the building models are indicated in Table 1. Using EPW weather data files, *DesignBuilder* utilized the weather and solar radiation data for the tropical region of Ogbomoso, Nigeria, to run twelve-months simulation cycles (i.e., January to December) to generate hourly, daily and monthly data outputs. Interior Solar Gains and indoor Comfort Temperature due to the alternative design options, obtained through Cooling Design Simulations for the study area are the simulation output variables considered relevant for the analysis. Thus, comparative impacts of each of the alternative design

options (as highlighted earlier) were analysed, to determine the most effective one for sustainable indoor thermal comfort and building energy efficiency.



Figure 1: Floor Plan of the Virtual Building Model

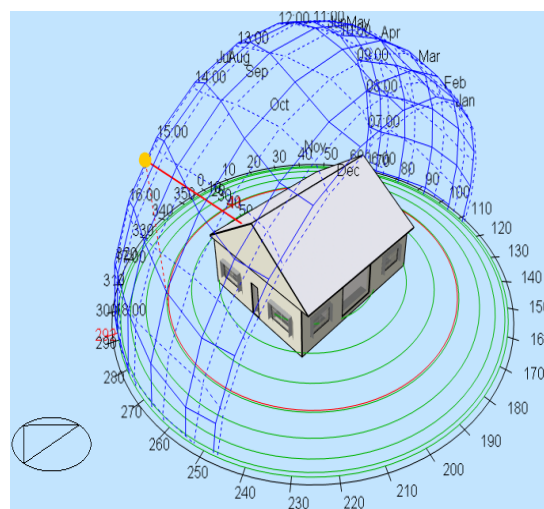


Figure 2: Virtual model of *Building I* on DesignBuilder simulation interface

Table 1: Thermo-physical Properties of the Varying Building Models as Adopted

Building Type		Control-Building	Shaded-Building	Double-G-Building	Low-E-Building
Window Category		Single Layer, Clear Glass	Single Layer, Clear Glass	Double Layer, Clear Glass, 13mm Argon filled	Single Layer, Low Emissivity (e2=.2) Metallic Coating Glass
Number of Pane Layers		1	1	2	1
Thermal Properties	Thickness (mm)	6.000	6.000	6.000	6.000
	Conductivity (W/m-K)	0.900	0.900	0.900	0.900
	U-Value (W/m ² -K)	5.778	5.778	2.511	3.779
	Solar Transmittance	0.775	0.775	0.775	0.680
Solar Properties	Outside Solar Reflectance	0.071	0.071	0.071	0.090
	Inside Solar Reflectance	0.071	0.071	0.071	0.100
	Visible Transmittance	0.881	0.881	0.881	0.810
Visible Properties	Outside Visible Reflectance	0.080	0.080	0.080	0.110
	Inside Visible Reflectance	0.080	0.080	0.080	0.120
	Infra-Red Transmittance	0.000	0.000	0.000	0.000
Infra-Red Properties	Outside Emissivity	0.840	0.840	0.840	0.840
	Inside Emissivity	0.840	0.840	0.840	0.200
	Total Solar Transmission	0.819	0.819	0.704	0.720
Solar Properties	Direct Solar Transmission	0.775	0.775	0.604	0.680
	Light Transmission	0.881	0.881	0.781	0.811

(Source: [35])

III. Results and Discussion

A. Analysis of the solar radiation with its design implications for the study area

In view of the geographical location of the study area vis-à-vis the simulation output, relevant climatic attributes of the study area with regard to the Outside Dry Bulb Temperature and Solar Radiation (considering both direct and diffuse) are presented in Figure 3. Within this context, the focus is on the solar radiation trend as it forms the basis for the indoor solar gains, the consequence of which may result in thermal discomfort within the building by the occupants. From Figure 4, it could be observed that high solar radiations are recorded particularly, between October and May, with each month experiencing almost 100 kwh/m² area of *Diffuse Radiation*. A similar trend is observed in the *Direct Radiation* over the same period. The month of March witnessed highest *Diffuse* and *Direct Radiations* of 114.13 kwh/m² and 84.45 kwh/m² respectively. Details of this simulation output as captured directly from

DesignBuilder interface is as shown in Appendix I for referencing and verification.

B. Building Indoor Thermal Experience Before the Intervention

Arising from the solar radiation pattern in the study area as observed in the previous section, simulation output from the Control Building (i.e., the building without any design/material intervention) as shown in Figure 4 indicates annual solar gains of 18410.32 KWh through the exterior windows in the building, with the maximum and minimum of 1839.85 KWh and 1321.21 KWh recorded in the months of January and September respectively.

These values form the basis of the indoor thermal experience (i.e., indoor thermal comfort or discomfort) from which comparisons are made with the performance trend after the various interventions (as defined in the research methods).

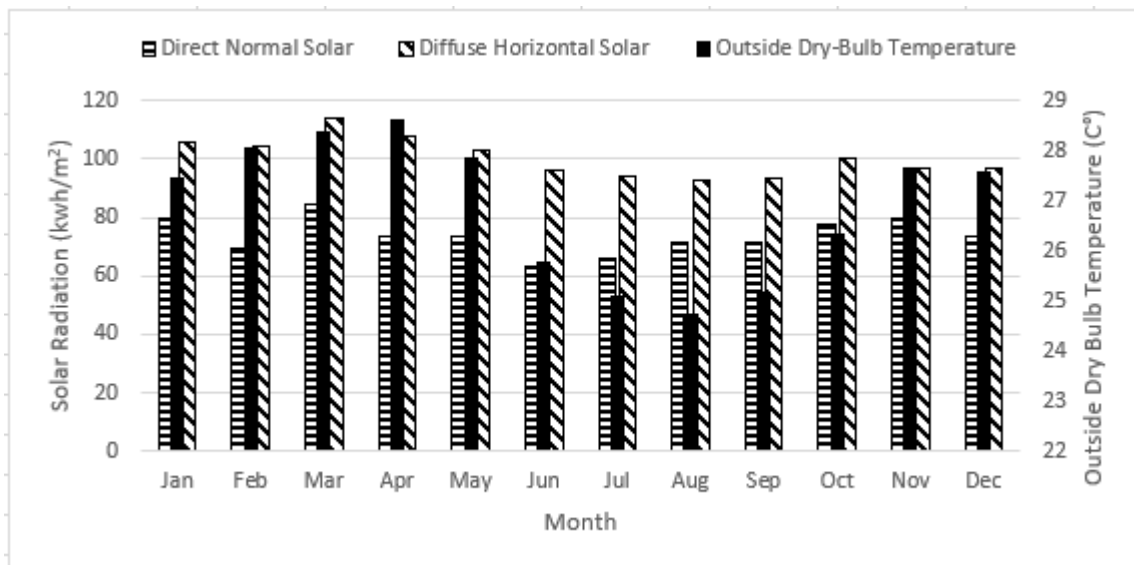


Figure 3: Simulation Output showing *Outside Dry Bulb Temperature* and *Solar Radiations* (involving both direct and diffuse) of the Study Area

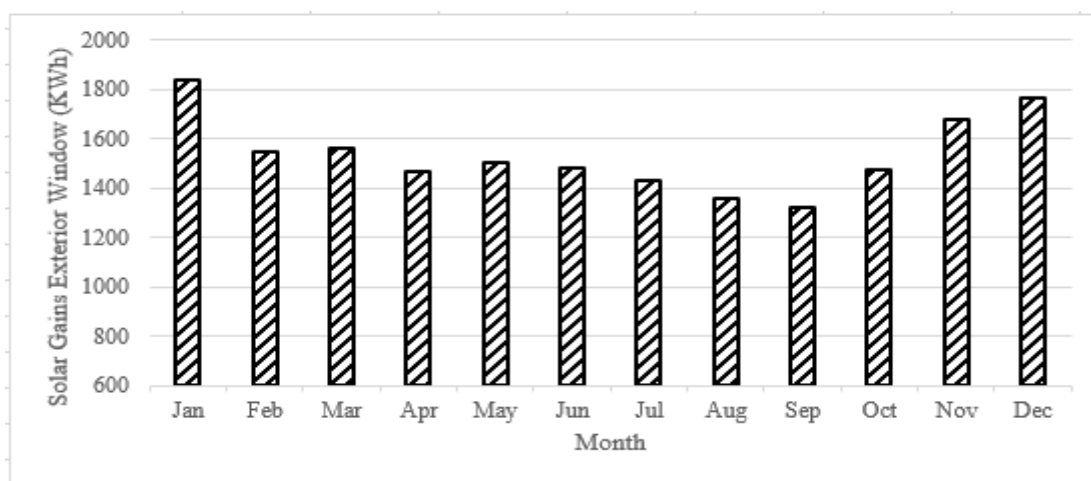


Figure 4: Monthly building Solar Gains through the Exterior Glazing

C. Building Indoor Thermal Experience After the Interventions

The focus of this research is to compare various design/material interventions to inhibit indoor solar gains with a view to improving building energy efficiency, for attaining sustainable indoor thermal comfort in the study area. As stated in the research method, these interventions involve comparative assessments of three sustainable approaches involving adoption of Fixed External Shading Elements (using **Shaded-Building** model), introduction of double-glazing windows (using **Double-G-Building** model) as well as coating of the window glass surfaces with a low-emissivity material (using **Low-E-Building** model). Results of these interventions are thereby presented. Figure 5 shows these comparative simulation outputs for the design/material interventions, as captured on a typical hottest day in the study area (i.e., 30th of April). Based on the changing position of the sun, the impact of the solar radiation is observed as the Diffuse Horizontal Solar Radiation gradually picked from 0.15729 W/m² in the morning (at 700 hrs) to reach the peak (0.912943 W/m²) around mid-

day (1300 hrs) with its impacts on each of the buildings, in respect of the Solar Gains through the Exterior Windows. While the impact is most felt on the *Control Building* designed without any intervention (i.e., recording 1.682366 KWh and 5.869765 KWh at 700 hrs and 1700 hrs respectively), the attenuating effects of the double glazing is observed in *Double-G-Building* (recording 1.438875 KWh and 5.014295 KWh at 700 hrs and 1700 hrs respectively). This is followed by the Shaded Building and the least protected building with the intervention, the *Low-E-Building*. The same trend is observed in their annual performance as captured in the Annual Simulation output shown in Figure 6.

D. Overall Results Implications

Based on the observed results above, tropical region is characterised with high solar radiation with its negative impacts on the building indoor thermal condition. Hence, there is the need for a mechanism to attenuate this impact on the interior living condition of the building occupants. From this investigation, beneficial effects of double-glazing of the window panes as the most effective solar radiation penetration control strategy (through the openings),

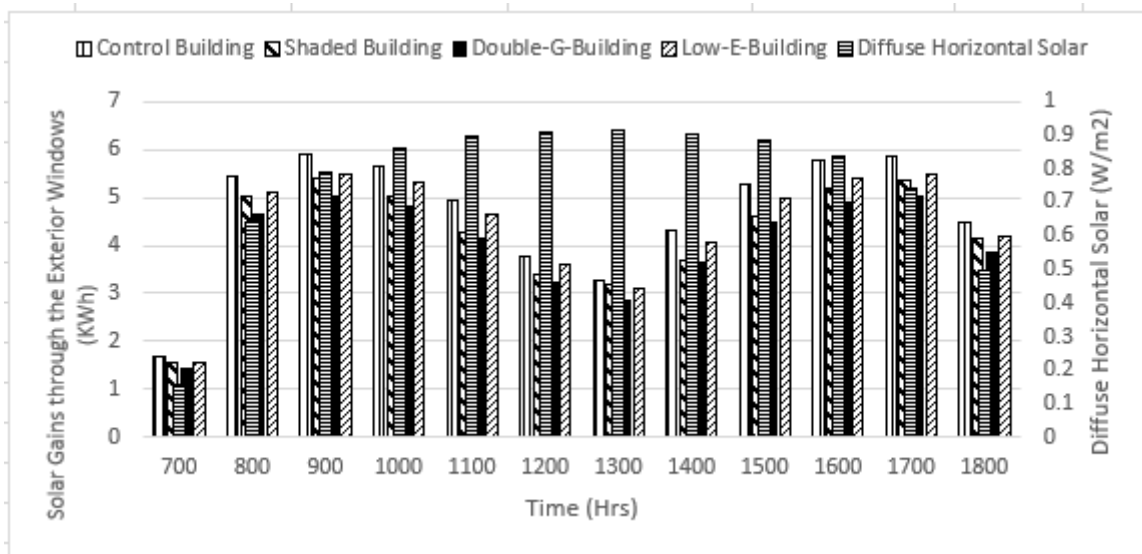


Figure 5: comparative Solar Gains through the Exterior Windows for each of the Building Models (with the Design/Window Material Intervention) on a typical Peak Summer Day (i.e., Hottest Sunny Day) relative to the general Outdoor Diffuse Horizontal Solar Radiation

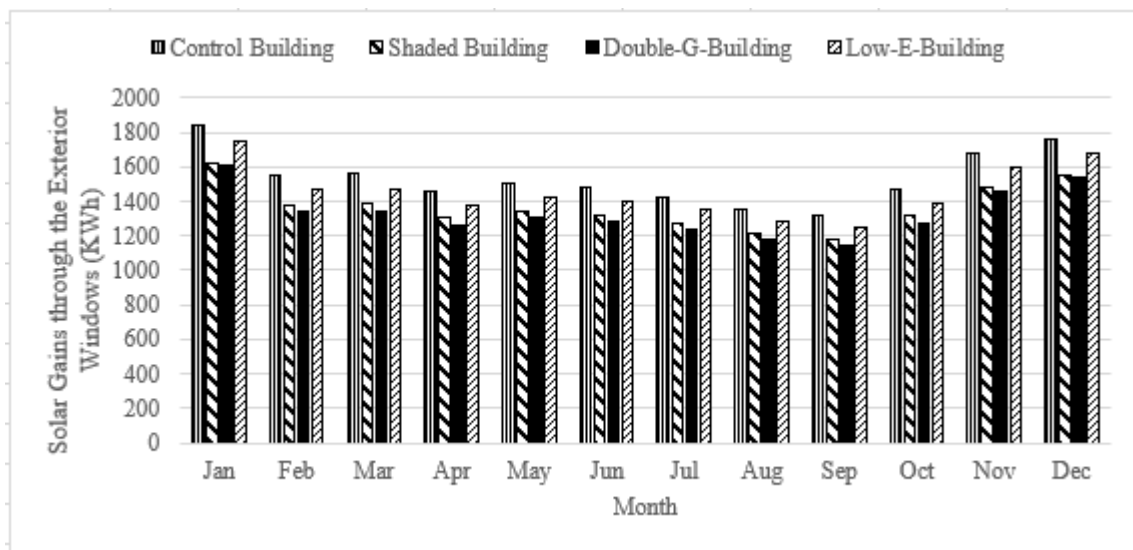


Figure 6: Comparative Annual Solar Gains through the Exterior Windows for each of the Building Models (with the Design/Window Material Intervention)

followed by integration of fixed sun shading elements on the exterior parts of the building are established. These research outputs align with the findings of [7], [12], [17], [24], [25], [36], [37], among others. It is therefore advised that adoption of double or more layers of glass panes in controlling indoor solar radiation penetration should be encouraged. Where this is practically difficult, integration of external window shading elements could be adopted. In general, the two approaches indicate sustainable Solar control strategies that can be considered for all glazed openings exposed to direct sunlight particularly, the

IV. Conclusion

One of the hallmarks of Tropical region is its high solar radiation with its attendant high solar gains through the exterior glazing units particularly, the windows. This forms the basis of the region's peculiar indoor thermal discomfort. Thus, efforts are made towards reducing the amount of solar gains to minimise its impacts without compromising the beneficial effects of daylighting and visual comfort. This research in form of a computer-based simulation was therefore carried out with a view to evolving sustainable mechanism for reducing the solar gains into the interior. From the identified three comparative approaches within this context, the results of the investigation on a typical tropical residential building design in the study area of Ogbomoso, Nigeria, indicate adoption of double-glazing for the windows as the most effective. This is followed by integration of fixed external window shading elements, and adoption of low emissivity glass coating as the least effective of the three approaches. These efforts aim at improving building energy efficiency through sustainable

design approaches for overall safe global environment.

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Appendix I

Details of the Site Data simulation output (including Outside Dry Bulb Temperature and Solar Radiation (involving both direct and diffuse)) as obtained directly from DesignBuilder interface

