Achieving Visual Comfort through Solatube Daylighting Devices in Residential Buildings In Nigeria

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Abstract—There are different methods of achieving visual comfort in residential buildings. Some of the methods include the integration of electric lights, curtain walls and skylights among many others into either the façade or roofing systems of buildings. However, this paper puts forward a study of the use of Solatube daylighting devices - a type of tubular daylighting device, in achieving excellent levels of visual comfort. A proposed residential building with walls and roof made of concrete blocks and asphalt shingles respectively was taken into consideration because most buildings in Nigeria, especially the residential types, are made of these materials. The findings of the lighting analysis for the residential building are presented in this paper. The analysis was focused on the roof of the building and carried out using the Light Analysis Revit (LA/R) plug-in. Over the years, climatic data has shown that most areas in the South Western part of Nigeria receive great measures of sunshine. The same is true currently. It is even truer that these high levels of sunshine can be optimized using Solatube daylighting devices in the roofs of residential buildings.

Index Terms—Tubular daylighting devices, residential building, solatube daylighting devices, false-colour chart, light tubes, illuminance, lighting analysis.

1 Introduction

The increasing awareness on the concept of net zero - energy building as well as sustainable buildings has led to a corresponding increase in the usage of tubular daylighting devices in various typologies of building projects including infrastructure and industrial architectural projects. For instance, Solatube International Incorporated, a company known for the production of tubular daylighting devices has been able to market its products to factories, offices, schools, health care facilities and single family homes in major countries of the world.

The tubular daylighting device which uses a reflective material was once fully utilized by the ancient Egyptians. Now that the daylighting system has been patented by Solatube International Inc., the company has gone on to make several structural changes along the years in response to customers' demands. The daylighting device was appraised as a roof system by the Building Research Association New Zealand (BRANZ) within certain scopes.

The scopes include the limitations of a building's height as well as maximum floor areas, building structures which meet the design and construction requirements of the NZBC, location in wind zones, types as well as profiles of roof cladding and usage of daylighting systems on flat roofs [6]. The Solatube daylighting device was appraised based on the aforementioned under the clauses of durability, external moisture, ventilation, hazardous building materials, natural light and energy efficiency.

According to the BRANZ Appraisal document, Solatube daylighting devices can be installed in different roof types such as corrugated iron or long run iron, concrete tile, pressed metal tiles, terracotta tile, butanol or membrane roofs, corrugated iron or long run less than 5 degrees in pitch and asphalt or slate tiles although the document specified the 250 mm Solatube daylighting devices as suitable for these roof types [6].

A basic Solatube daylighting device is commonly tripartite and comprises essentially of a dome, which serves as the entrance for the sun's rays, a long or short tube that helps to transfer the light rays down to the diffusers, which help to spread the light rays into a space. Figure 1 depicts what a typical Solatube daylighting device looks like.

Fig. 1. A section through the roof of a building with a Solatube daylighting device

Visual comfort can be achieved by allowing more of natural daylight into buildings and giving occupants of a space control over the lighting in a building which are some of the benefits a Solatube daylighting device offers. Although Solatube daylighting devices have small areas in terms of their diameters, they give out large portions of useful light which maximizes energy savings [13].

An instance of an energy savings analysis can be seen in the research conducted in an underground parking space in China, where daylight coefficient calculations were done to determine the efficiency of tubular daylighting devices based on the daylight climate data for Beijing. It was discovered that daylight could be introduced into poorly lit environments while saving energy, although the research carried out was done under standard clear and cloudy skies [16].

The scope, in terms of physical dimensions and building typologies can be adequately covered by the use of Solatube daylighting devices. In a test carried out on double - loaded educational buildings in the Jordan University of Science and Technology (JUST) in Jordan as shown in Figure 2 below, it was discovered that light tubes can provide adequate daylight in upper floor levels with lobbies [11].

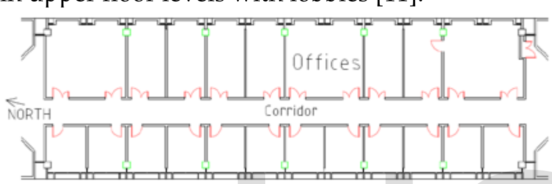


Fig. 2. The double - loaded corridor in JUST engineering buildings

It is important to note that there are two major types of light tubes – horizontal and vertical light tubes. Horizontal light tubes or pipes (HLP) can be used to channel natural light from the external environment through the façade to the internal environment of a building. They are usually used in multistory buildings. Vertical light tubes or pipes (VLP) are used in the roof of buildings, especially those with middle rise deep plans [12].

Horizontal light tubes and vertical light tubes exhibit certain differences in terms of their design. These differences are found in the forms of their Light Collecting Panels, light extraction and considerations for design [12]. Although the side lighting of the horizontal light tubes goes down faster than the vertical light tubes, vertical light tubes are able to receive and move more light than the horizontal light tubes under sunny days in places like Beijing [7].

The Leadership in Energy and Environmental Design (LEED), which is a rating system developed by the Green Building Council in the United States is applied to buildings in order to gauge their levels of sustainability. The utilization of Solatube daylighting systems in buildings is usually part of the reason(s) why such buildings gain the LEED certification [15].

2 Literature Review

It is expedient to understand the difference between the terms: 'sunlight', 'daylight' and 'daylighting' as well as 'illuminance' and 'luminance'. 'Sunlight' is a term used to describe the direct light from the sun and occurs mostly at the noon time of a day. The illumination and heat of the sun are usually felt during these times. On the other hand, 'daylight' refers to the quality of light that provides satisfactory illumination during daytime [10]. It is made up of the direct and indirect light of the sun.

'Daylighting' describes the medium or media through which daylight is admitted into a space. The quantity of sun's rays hitting a surface can be described as illuminance while luminance describes the sun's rays that are being reflected off a surface. Illuminance can be measured in lux (lumens/m^2) or footcandles (lumens/ft^2). For instance, an electric light bulb will sometimes show the number of lumens required to pull an amount of electric power [14]. In other words, the level of brightness of a bulb is equal to its lumens. According to *Abd Kadir et al.* [1], daylighting was described as a method to lighten up the interiors of buildings using natural light without the use of artificial lighting during the day.

Stemming from the early times of the 18th century, artificial lights have always played a supporting role to natural light. However, after this period, there seemed to be a reversal in the roles of artificial and natural lights in buildings when advancements in technology made it possible to create a vast majority of artificial lights such as fluorescents and electric bulbs. Now, due to the exposure of designers to concepts of sustainability and green architecture, natural lights are taking the lead role in contemporary designs and constructions. To further aid the concept of sustainability, in line with [2], a retrofit strategy which involves the integration of photovoltaic panels into the form of a structure has been employed in different variations of the Solatube daylighting device.

Daylight is very important in building spaces as it has been linked to high levels of productivity, better moods, minimized absenteeism, better job satisfaction, improved assimilation ability for students and improved aesthetic values of buildings [8]. The effects of daylight on people are numerous and human responses to daylight ought not to be ignored because architectural designs aim at making the occupants of a space comfortable thermally as well as visually. *Abd Kadir et al.* [1] described the benefits that are derived from daylighting by people. Daylighting provides people with a "favourable perception of colour". In other words, daylighting provides users of a space with expressive and fascinating visual qualities.

The performance of workers is enhanced due to sufficient daylighting in an office space, allowing workers to experience visual comfort. Cooling loads are reduced substantially through the employment of effective daylighting strategies. Using large windows in a building space helps to bring in maximum daylight but most of the time, this can prove to be a huge disadvantage due to the excessive heat losses or gains by the building *Abd Kadir et al.* [1].

As stated in [5], the loss and gain of heat through windows affects the thermal comfort of offices. This means that Solatube daylighting devices can indirectly help to deal with the issue of heat gain or loss because they are sealed in their domes with special materials that possess great insulation properties. In [3], it was discovered that there was overheating of the interior spaces due to excessive radiation from the sun. A Solatube daylighting device in this case resolves this issue.

Recent calculations performed by the National Research Council of Canada have come up with five guidelines for manufacturers and installers in relation to the use of tubular daylighting devices. The location of a building, day and year affects the lighting performance of tubular daylighting devices with bends. The light transmittance of a tubular daylighting device is affected by the type of elbows present in it. The orientation of light guides determines the kind of results that are attained.

Unbent vertical pipes deliver more efficiently than bent ones when the sun is at angles lower than 60° and less efficiently when the sun is at angles greater than 60°. Bent guides oriented towards the north give the lowest transmittance when the sun is at angles lower than 32° and highest transmittance when the sun is at angles between 32° and 60° [13].

In order to be able to assess or better still predict the daylighting performance of light tubes, certain tools have to be used such as scale models. It is essential to predict daylighting performance of light tubes because of two major issues that arise with respect to buildings, especially in the tropics. They are the high electricity utilization due to artificial indoor lighting and underutilization of natural daylight for lighting up the interior of buildings during daytime [4]. Due to the peculiar nature of tropical countries where long hours of sunshine are experienced, there is a great advantage in using light tubes or pipes as sources of natural light in buildings.

In a study conducted on a building model in Malaysia, it was discovered that light tubes or pipes that had low aspect ratios exhibited a good diffusing performance as these pipes allowed the transmission of light to bigger aspects of the rooms in which they were placed. The light pipes that exhibited a good diffusing performance had aspect ratios as low as 6.0, 5.8 and 5.0 and their diameters as 2.5 cm, 3.0 cm and 3.5 cm respectively.

It is interesting to note that light diffusers and collectors were not used in the project even though it was conducted in a dark room [4]. The results of the experiment carried out in the project were arrived at through the use of the conversion factor which shows how reliable a system used to predict light tube performance is. Therefore, a conversion factor complements whatever scale model is used in a light pipe experiment [4].

3 Methodology

This part of the paper deals with the system of methods used to carry out this project. Light Analysis Revit (LA/R) plug-in which used to be known as Revit Daylighting Analysis (RDA) was used to carry out the lighting analysis in the proposed residential building. The rendering system employs a cloud service to calculate and simulate scenes in a building model. The concept and atmospheric conditions used in the analysis are explained further below.

As a basic concept, the idea was to carry out an analysis of the proposed residential building (two units of 1 + 1 apartments sharing a common wall) for two individuals.

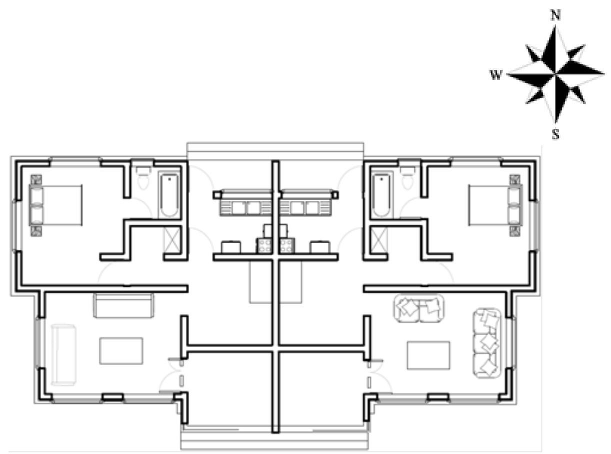


Fig. 3. Floor plan of the proposed residential building in Lagos, Nigeria

Studies of the proposed building were done before and after the Solatube daylighting devices were installed in the roof of the building at two different times (9 am and 2 pm) of two months (March and August). These two months were chosen because they possess the highest and lowest temperatures in average respectively as can be seen in the table below.

Table 1. The climate data for Lagos, Nigeria

	January	February	March	April	May	June	July	August	September	October	November	December
Avg. Temperature (°C)	27.5	28.2	28.6	28.2	27.5	26.4	25.7	25.2	25.7	26.3	27.4	27.4
Min. Temperature (°C)	23.3	24.8	25.4	24.8	24.3	23.3	23.2	22.7	23.2	23.3	23.8	23.8
Max. Temperature (°C)	31.7	31.7	31.8	31.7	30.7	29.5	28.3	27.8	28.3	29.4	31.1	31.1
Avg. Temperature (°F)	81.5	82.8	83.5	82.8	81.5	79.5	78.3	77.4	78.3	79.3	81.3	81.3
Min. Temperature (°F)	73.9	76.6	77.7	76.6	75.7	73.9	73.8	72.9	73.8	73.9	74.8	74.8
Max. Temperature (°F)	89.1	89.1	89.2	89.1	87.3	85.1	82.9	82.0	82.9	84.9	88.0	88.0
Precipitation / Rainfall (mm)	25	43	97	140	251	386	248	74	161	177	70	21

Table 2. The atmospheric conditions under which the test was taken.

CONDITION	DETAIL
Location	Lagos, Nigeria
Times at which tests were taken	9 am and 2 pm

Dates used in the test	March and August 2, 2010
Global Horizontal Irradiance (GHI)	95 - 885
Direct Normal Irradiance (DNI)	138 – 833
Diffuse Horizontal Irradiance (DHI)	21 – 97 W/m^2

NOTE: The Global Horizontal Irradiance refers to the total quantity of radiation received by a ground surface. This information can be useful when dealing with photovoltaic panels. The Direct Normal Irradiance and Diffuse Horizontal Irradiance make up the Global Horizontal Irradiance.

Other conditions are that the threshold range for the analysis was between 0 to 3000 lux while an analysis plane height of 37 inches above floor level was used.

4 Findings and Discussions

After carrying out a lighting analysis of the proposed residential building, the following results were arrived at. The false-colour in Figure 4 below was used as a yardstick for the lighting analysis done on the proposed residential building. It helped to determine how well the target spaces (the lobby, entrance to the room and toilet) were improved in terms of lighting.

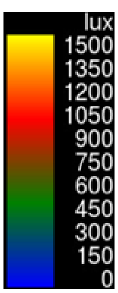


Fig. 4. A false-colour chart showing the range of illuminance levels guiding the analysis

The figures below show the results for the proposed residential building in March, June, August, September and December in Lagos, Nigeria. Observations are given alongside the tables.

Figures 5 and 6 show the results for March, which has the highest temperature level among the other months. A little period after 9 am in the morning, the target spaces experienced daylight after the Solatube daylighting devices were introduced into the building's roof. Another observation from the figures was that the lighting in the building before the two o' clock hour was quite better than the period after.

	9 am	
	Before Installation of Solatube	After Installation of Solatube
March 2nd		

Fig. 5. Two different colour charts shown for the second day of the month of March at 9am

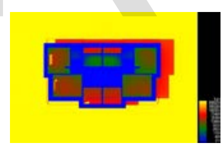
	2 pm	
	Before Installation of Solatube	After Installation of Solatube
March 2nd		

Fig. 6. Two different colour charts shown for the second day of the month of March at 2 pm

Figures 7 and 8 show the results for June, which has an average temperature of 26.4 °C and highest rainfall/precipitation of 386 mm according to Table 1. Before the installation of the Solatube daylighting device, the corridors and room entrances were noticeably dark. However, after the installation of the device, the light in the spaces become adequate for the occupants of the residential building.

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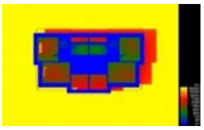
	9 am	
	Before Installation of Solatube	After Installation of Solatube
June 2nd		

Fig. 7. Two different colour charts shown for the second day of the month of June at 9 am

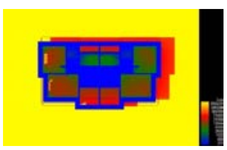
	2 pm	
	Before Installation of Solatube	After Installation of Solatube
June 2nd		

Fig. 8. Two different colour charts shown for the second day of the month of June at 2 pm

Figures 9 and 10 show the results for August, which has the lowest temperature level among the other months. After the Solatube daylighting devices were installed in the roof of the building, the lighting in the building during the period after 9 am in the morning also seemed better than the period after 2 pm. This is because the sun at 2 pm is already showing signs of setting which results in lower levels of natural daylight in the building.

	9 am	
	Before Installation of Solatube	After Installation of Solatube
August 2nd		

Fig. 9. Two different colour charts shown for the second day of the month of August at 9 am

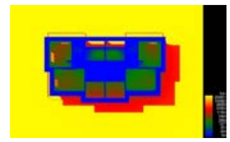
	2 pm	
	Before Installation of Solatube	After Installation of Solatube
August 2nd		

Fig. 10. Two different colour charts shown for the second day of the month of August at 2 pm

Figures 11 and 12 show the results for September, which has an average temperature of 25.7 °C and rainfall/precipitation of 161 mm. It is interesting to note that just like the month of June, the high rainfall experienced in this month did not affect the lighting performance of the Solatube daylighting devices installed into the residential building.

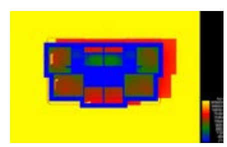
	9 am	
	Before Installation of Solatube	After Installation of Solatube
September 2nd		

Fig. 11. Two different colour charts shown for the second day of the month of September at 9 am

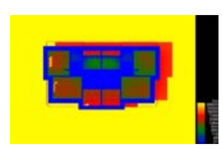
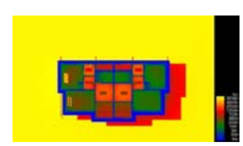
	2 pm	
	Before Installation of Solatube	After Installation of Solatube
September 2nd		

Fig. 12. Two different colour charts shown for the second day of the month of September at 2 pm

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Figures 13 and 14 show the result for December, which has an average temperature of 27.4 °C and very low rainfall level of 21 mm. Again, there is a noticeable difference in the performance of the Solatube daylighting devices as in the months above as the illuminance level in the morning around 9 am is higher than the illuminance level around 2 pm.

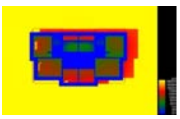
	9 am	
	Before Installation of Solatube	After Installation of Solatube
December 2nd		

Fig. 13. Two different colour charts shown for the second day of the month of December at 9 am

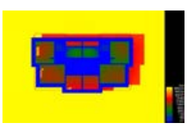
	2 pm	
	Before Installation of Solatube	After Installation of Solatube
December 2nd		

Fig. 14. Two different colour charts shown for the second day of the month of December at 2 pm

From the above pictures, the dependence of the residential building on external illuminance is conspicuous. With the movement of the sun in the morning around 9 am, the residential building experienced a better influx of light as the solar latitude increased compared to the internal illuminance that was experienced at 2 pm.

At the peak hour which is noon time, the external illuminance is greatest and is the period at which most spaces in the building were lit up. In agreement with *Abd Kadir et al.* [1], there is a close relationship between climate and the efficiency of tubular daylighting devices, as the sky conditions can affect the performance of light tubes either positively or negatively.

Additionally, from the above pictures, there is clear evidence that the use of Solatube daylighting devices in the building helped improve its lighting. The spaces in the building marked blue are the lobby, entrance to the room and toilet. These spaces have little or no light because they are located deeply within the building. From the false - colour bar, the illuminance levels of these spaces are not more than 50 lux. However, with the integration of Solatube daylighting devices, as seen on the right hand side of the tables, there was an increase of over 1150 lux indicated by the shade of yellow in the space previously shaded blue.

To understand the results better, false - colour diagrams and normal rendered views of the lobby, room entrance and toilet spaces in the residential building were developed and shown below.

Fig. 15. False-colour chart of the lighting in the entrance to the room

Observation - The entrance to the room is well-lit up due to the integration of the Solatube daylighting device. The illuminance level helps to improve the mood of the user of the space even before entering the bedroom.

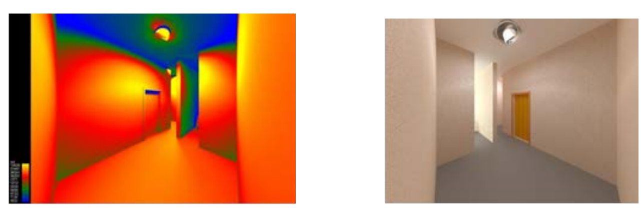


Fig. 16. False-colour chart of the lobby in the residential building

Observation - The light provided by the Solatube daylighting device has been diffused throughout the entire lobby. The lobby, which is located in the core of the residential building can help distribute light to other parts of the building.

Fig. 17. False-colour chart of the lighting in the toilet

Observation - The bathroom has a small window which provides inadequate light. However, with the integration of a Solatube daylighting device, the light in the space becomes sufficient for the user.

Using Solatube daylighting devices with tube size (diameter) of 250 mm generated the above results. The Light Coverage Area of the Solatube daylighting device used in the tests above is 10 m^2 which is just sufficient for the lobby, entrance to the room and toilet as they have their spaces as 9 m^2, 3.78 m^2, and 3.42 m^2 respectively. Tests which were taken for other dates in the months of March and August showed the same results as the dates used (March and August 2nd) in this analysis.

5 Conclusion

The use of Solatube daylighting devices in different building typologies is fast becoming a trend in the construction industry. Besides being a source of natural daylight, it provides a form of 'healthy' daylight to residents in a building space. In other words, the glare or heat associated with the sun's rays is filtered off unlike the traditional skylights which contribute to heat gain and glare and result in eye strain and the fading off of soft furnishings. There are still innovations in the lighting industry which is a positive sign that better solutions will come up.

Contrary to [15], Solatube daylighting devices are cheaper to procure and install compared to traditional skylights even though they deliver equal light output. They help to keep insulation in residential buildings. This is a useful device for residential buildings located in cold climatic regions. The maintenance costs that accrue from usage of Solatube daylighting devices are very low. This is hugely due to the fact that they are designs that come as one piece and have impact-resistant properties.

Possible extensions of the project can happen based on the form of tubular daylighting devices. Most likely, there will be better adaptive forms of tubular daylighting devices in the nearest future which will give rise to a wide range of discussions on the concept of sustainable buildings. For instance, user control over the amount of light channeled through the Solatube daylighting device can be worked upon towards ensuring maximum visual satisfaction.

Most residential buildings in Lagos, Nigeria tend not to have daylight solutions for spaces located deeply within the house and therefore have to rely on artificial forms of light like the electric lights. Hence, developing tubular daylighting devices for such houses will not only make them sustainable or energy-efficient but also a comfortable place for their occupants to live and work in.

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