SAJSET
ISSN: 2992-3581

Savannah Journal of Science and Engineering Technology
Volume: 01; Issue: 04; Pages: 111-122; 2023.
www.sajsetjournal.com.ng
DOI: xx.xxxx.x/sajset-01-2023-0036

SAJSET
ISSN: 2992-3581

# Optimising indoor lighting condition for visual comfort via light pipes in design of Kada-city shopping mall

[1]Zarewa, Y. D., [1]Tukur, R. B. and [2]Abdulhamid, F.
[1]Department of Architecture, Ahmadu Bello University, Zaria.
[3]Department of Architecture, Modibbo Adama University, Yola.

**Paper History**
*Received: 05th July, 2023*
*Accepted: 30th July, 2023*
*Published: August, 2023*

*Corresponding author*
Abdulhamid, F.
abdulhamidfahad@mau.edu.ng

**Abstract:**
*With increasing cost of electricity and epileptic state of electricity supply in Nigeria, it has become a necessity to harness day lighting in shopping malls, but with the advantages of daylight follows the problems of inadequate placements of openings, which brings about overheating, under-lighting, over-lighting and glare which makes planning of buildings so that daylight could enter interior spaces a huge problem. The aim of this study is to determine the optimum diameter of light pipe for a daylighting of shopping malls in Kaduna metropolis with the view of designing Kada city shopping mall using its findings. Qualitative research methods were employed using computer simulation software using climate data gotten from meteorological data sets. Results showed that the quantity of day lighting is affected by a change in diameter of light pipe. An 85% increase in average lux levels from 794.4 lux at no light pipes to the 1469.2 lux at 450mm diameter light pipe with a 36% increase in Daylight autonomy (DA) from 37% at no light pipe to 73.2% at 300mm diameter light pipe. In conclusion, 300mm diameter of light pipe was found to be the optimum diameter for adequate lighting of shopping malls in tropical climates of Nigeria. Due inadequate values (below 60%) together with UDI values were observed in all the simulation models with light pipe diameters below 300mm, it is recommended that designers should use 300mm diameter light pipes in every 12m$^2$ area.*

**Keywords:** *Daylighting, Daylight autonomy, Useful daylight illuminance, light pipes, Shopping mall*

## 1. Introduction

The primary functions in any building can only be carried out within an envelope providing adequate visual and thermal comfort easing communication. The use of daylight for indoor task illumination has been widely advocated so it's a task for the architect, to balance the different environmental parameters with the design variables [1].

Prior to the invention of electric light, and for a good while after that too, planning buildings so that daylight could enter interior spaces was a huge necessity. Regardless of a long history of using day lighting as design strategy, building owners, architects, engineers and lighting designers are only just beginning to understand how to use it effectively. Researchers such as Tragenza and Wilson [1], Reinhart [2] and Leslie [3] have established over the years that lighting is a major factor in determining the way in which people experience the internal environment, how they experience buildings, as well as how they are able to respond to certain tasks. Erlendsson [4] opined that using daylight as part of an integrated and controlled lighting strategy is a key component of a sustainable, environmental approach to architectural design.

Shopping Malls are places used all day long, as such daylight is of paramount importance to be used at daytime, limiting the expensive artificial lighting usage to night times. In places that need high levels of lighting like shopping malls, day lighting is very important in order to display products in true colours and provide consumer's visual comfort. Perception of products colour and texture truly is only possible with daylighting. Thus, daylighting is an optimum solution for complete shopping experience. Recent trends on shopping malls designs are a fully glazed unshaded facades which are affected by excessive solar heat gains, which turns in high cooling energy consumption and visual discomfort. This in an attempt to make it look sophisticated and admit light into the indoor environment, increasing the glazing ratio of the entire building envelope. Nonetheless, this action has not solved the over reliance on fossil fuel and provision of a well-lit indoor shopping hall as observed in the most shopping mall within the country [5].

The source of daylighting as well as its management in public buildings is a major consideration in the area of building sustainable environments. The primary aim of providing buildings with continuous natural light is also reinforced by the need to improve occupant's comfort. Thus, it is important for architects to research and appreciate the manner in which visual comfort in interior of shopping malls is achieved by daylighting to reduce the energy usage in buildings. This will help in identifying ways in which we could attempt to reduce our dependency on fossil-fuel, considering new forms of renewable technologies and thus, create an indoor environment which is safe for man visually, hygiene wise and also cost efficient [5].

This research explores the use daylighting with a view to achieve optimum indoor lighting condition for human visual comfort reducing the consumption of fossil-fuels which give off emissions that contribute to global warming. This is especially useful in developing countries where there are frequent power outages as well as lack of cost-effective energy services. Of all the available daylighting systems, light pipes and fibre optics have the greatest capacity to allow light to penetrate a considerable distance into the building envelope [6].

## 2. Literature Review

### 2.1 Daylighting

Daylighting can be defined as that visible light which is emitted via the electromagnetic radiation from the sun [7]. Daylighting is preferred to artificial lighting as it boosts productivity [8]. Lack of daylight exposure for a long period of time is found to cause mood swings and depression [9]. The term "daylight", technically, means only sunlight diffused by particles and clouds in the sky. Daylight has been considered the most desirable light form due to its unique characteristics of continually changing patterns, advantageous for dynamic play on illuminating designed spaces, as well as its excellent efficacy [10].

The challenge of defining effective daylighting performance is often defined differently by different stakeholders in the design and use of the building. For example, a mechanical engineer may define performance in terms of electrical lighting energy reduction. Alternatively, an architect may define performance in terms of the aesthetic qualities of daylight distribution in the space. The client may define daylighting performance based on whether or not the project complies with the requirements of sustainable building certification criteria for daylight sufficiency and views. Also building occupants may judge the daylighting performance of the building based on their perception of daylight sufficiency, visual comfort, and available views.

#### 2.1.1 Architecture of Daylighting

Conceptually, daylighting can be distributed to interior space through openings from the side, from the top, or a combination of the two. Building type, height, massing, dominant climatic conditions, site obstructions and building functions are often drives choice of strategy [11]. Daylight can also be optimally implemented with innovative daylight systems. These make use of the physical laws of reflection and refraction to illuminate rooms perfectly and also to avoid excessive warmth [12]. The choice of strategies and the devices for optimum daylight therefore, depends on the functions of the buildings and the light requirement on each architectural space. The strategies are side lights, top lights, shedding devices, building orientation means of daylighting [11].

#### 2.1.2 Side lights as a means of daylight

Side lighting has been a primary way of introducing daylight into buildings. Besides supplying light, side lighting can provide view, create orientation, allow connectivity to outdoors, and allow ventilation during less harsh times of the year [13]. Openings and external controls should vary by compass direction since each facade of a building based on orientation receives different amounts of daylight throughout the day and across seasons. Location of openings in walls can be low, middle, or high depending on desired distribution and structural wall system restrictions [11]. Studies have listed sidelight strategies to include: Single side lighting, bilateral lighting, multilateral lighting, Clerestories, Light shelves, Louvers and blinds, Prismatic panels, light guiding shade [11, 14, 15].

#### 2.1.3 Top light as means of daylight

When daylight penetrates a building from above the ceiling plane or is concentrated in the roof, it is referred to as top lighting. Study by Baewon Koh and Meyer [12], shows that top lighting can provide greater freedom of source placement to achieve more uniform illumination. It takes advantage of high wall surfaces and other architectural elements to distribute light where needed and increases security and privacy. Splayed openings, for example, can spread the horizontal distribution of daylight over a wider area and reduce contrast associated with glare. The major restrictions for top lighting are the structural design, mechanical system, electrical system and fire safety layouts. Top lighting is of limited use in tall buildings because it can only illuminate upper floors, unless combined with other strategies [11]. Top lighting strategies include: Skylights, Roof monitor, Sawtooths, Courtyards, Atrium and Light tube [16].

#### 2.1.4 Shading devices as means of daylight

Shading is a strategy to reduce overheating and avoid direct sunlight into buildings. Moreover, problems associated with glare and visual discomfort are inevitable when direct solar radiation is transmitted into the interior spaces. Onuwe, *et al.* [17], clearly stated that to avoid overheating and glare problems, direct sunlight should not be allowed to enter into interior spaces. Shading provision is necessary to prevent thermal and visual discomfort. However, climatic conditions and daylight availability play a major role in the design and control of a shading system. Findings by Naseri [18], shows that location, properties and control of the shading device have a significant impact on both daylighting and thermal performance in perimeter of spaces. Similarly, studies by Jinia, *et al.* [19], shows that external shading devices have been utilized very intensively in the buildings of tropics to control the amounts of daylight and direct sun light flowing into interior spaces. Shading devices can be accomplished through different strategies like self-shading, overhangs on windows, building clustering, planting high trees, laser cut panels and designing shading features and some operable shading devices which give the flexibility of adjusting the shading shutters and blades to increase ventilation and day light into the interior spaces as well as minimizing the admittance of direct heat gain [20]. Shading usually obstruct daylight penetration, increase cost of lighting and HVAC. Shading is considered another significant design strategy that affects thermal comfort. Therefore, carefully design of shading system considering the climatic condition of the region is important [20].

### 2.1.5 Building orientation as a means of daylighting

Building orientation refers to the way a building is situated at site and the positioning of windows, rooflines, and other features [21]. Building orientation is considered the simplest and sensible design strategy that can be applied and effectively enhance light demand and performance in buildings. US DOE [22], climatic data revealed that buildings receive the highest amounts of solar gains in the hottest part of the year on eastern and western elevations, while in cold season the highest amount of light is received on the southern elevation. Jinia, Trisha and Mahmood [19], opines that the designers should also study microclimatic wind patterns of the site because they can help reduce heat gain and increase passive cooling and lighting. It's recommended to orientate buildings on the east-west axis with glazing designed to be located on the north and south sides of the building, supplemented with suitable shading devices for glare controls [21].

## 2.2 Daylighting system in Architecture.

Daylighting system consists of systems, technologies, and architecture as shown in figure 2.1, while all of these components listed by Ander [23] and Reinhart and Wienold, [24] may not be required for every daylighting system or design, one or more of them are typically present.

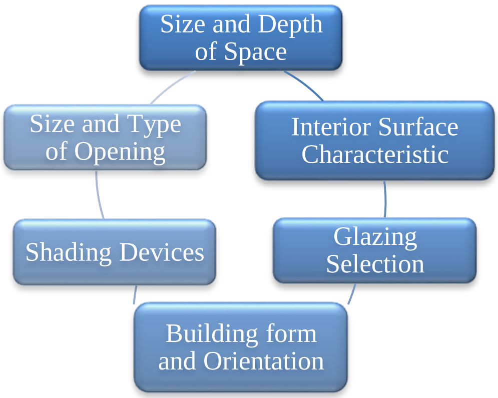


Figure 1: Systems of daylighting in architecture based on Reinhart and Wienold [24] and WBDG (2014)

### 2.2.1 Core Daylighting System

Core daylighting systems can supplement daylight from windows in deep spaces [25]. Some of the most common examples of core daylighting systems are: Skylights which are fenestration element located at a roof (plate I), Light wells are vertical spaces built on top of the roof to provide daylight and ventilation an open area or vertical shaft in the centre of a building, typically roofed with glass, bringing natural light to the lower floors or basement (plate II), Atriums are large open spaces located in the centre of the building (plate III), Hybrid Solar Systems (HSS) daylight is collected by a sun tracking collector (heliostat) and then transported by optical fibres to the luminaires(plate IV).

Plate I: Skylight from the roof top [25]


Plate II: Diagrammatic representations of light well [25]

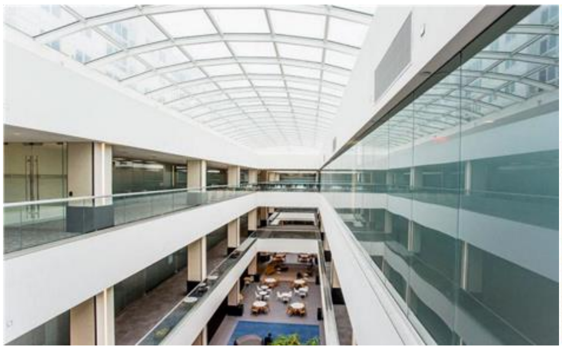

Plate III: Schematic sketch of Atrium [25]

Plate IV: Heliostat of a Hybrid Solar System [25]

### 2.2.2 Daylighting technologies, tools and devices

Daylighting technologies, tools and devices currently in use are heliostats daylighting devices, growth screen daylighting devices, fibre optics daylighting devices and light pipes daylighting systems which will all be discussed in details.

#### 2.2.2.1 Heliostats Daylighting Devices

Heliostats are stationary devices that track the sun shown in figure 2.1, usually to focus light towards a receiver of some kind. They are used for a variety of things from focusing more intense light onto photovoltaic, light telescopes and light transporting systems [26].

#### 2.2.2.2 Growth Screens Daylighting Devices

Growth green or vegetation screens are a natural way of controlling daylight, taking into account different lighting, heating and cooling requirements associated with changing seasons. Using deciduous plants allows more daylight and heat to enter the building during the colder half of the year, while blocking unwanted heat gains during the warmest season of the year [26]. They can often outperform fixed shading devices because of foliation growth triggered by temperature change. The vegetation responds to seasonal conditions that are warmer or cooler than average, while fixed shading devices are typically designed according to long-term average temperatures as seen in figure 2.2.

#### 2.2.2.3 Fibre Optics Daylighting System

Fibre optic collect using a rooftop collector (comprised of heliostats or lenses) and fed daylight into end of fibre optic cables that can run throughout the building distributing the light as shown in figure 2.3, Egan [26], findings shows that under full sunning conditions the cable can put out 1,180 lumens (about the output of a 100-watt incandescent bulb). Only the spectrum of light is allowed through the cable; the ultraviolet light and most of the infrared is filtered out. Some products only loss 4% of light per 10m of cable length. Allen, et al. [27], pointed out that the high cost of glass cable production makes this current technology impractical, but research is being done on using a less efficient but much cheaper plastic cable. Other research is being done on lowering different costs associated with fibre optic lighting. The current length limit is about 15m.

#### 2.2.2.4 Light Pipes Daylighting System

Light tubes (also known as sun scoops, tubular skylights, light pipe and solar pipes) are tubes or pipes used to transport natural light into an interior space as shown in figure 5. Light tubes allow is possible to get natural light into the dark core of a building or into underground structures. Light tubes are made up of three key components; the collecting head unit, the duct unit, and the diffuser unit [27]. The entrance to the tube is usually a dome, which acts to reflect the maximum amount of light into the tube. Mirrors and heliostats can also be employed to reflect light into the tube for better performance. The interior of the tube is highly reflective to help move light downward into the space with minimal loss. Some light pipe has up to a 90-98 reflection ability inside the tube [27].

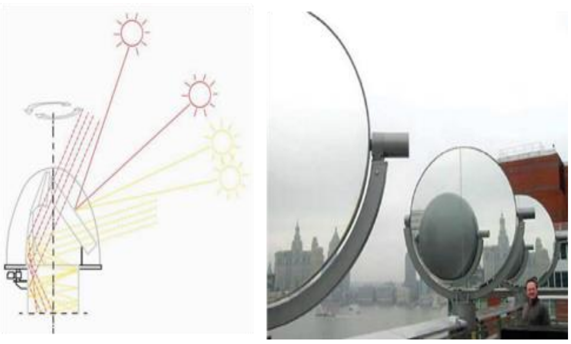

Figure 2.1; Diagram of Heliostats [27]

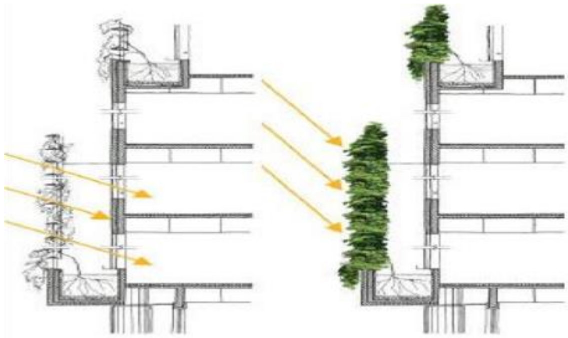

Figure 2.2; Growth green daylighting [27]

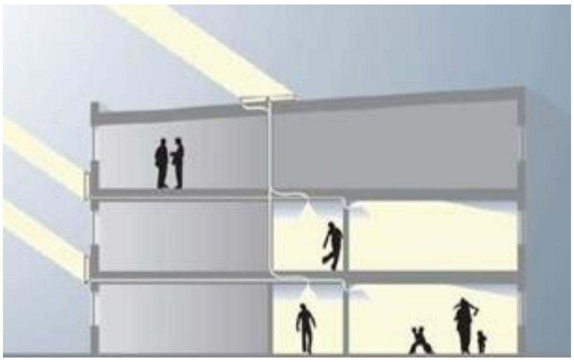

Figure 2.3; Fibre optics lighting technology {27]

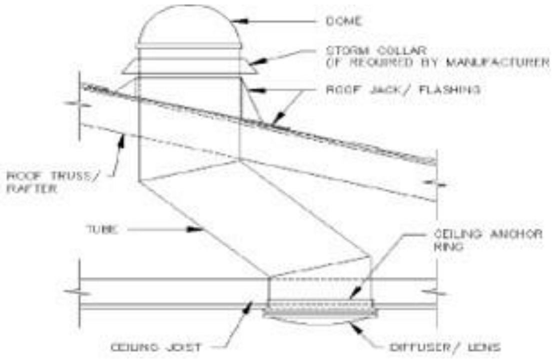


Figure 2.4; Section through a light pipe [27]

Throughout the world, there seems to be a number of barriers that hinder appropriate integration of daylighting aspects in the building design. However, it has been identified that some of the barriers to overcome [28], these three easily recognized major barriers are:

a. Lack of knowledge and information on new fenestration technologies and lighting control systems and the ability of such systems to enhance daylight utilization
b. Lack of convincing evidence that daylighting can substantially improve energy efficiency and visual quality in buildings
c. Lack of appropriate and user-friendly daylighting design tools including models for innovative daylighting systems and controls

Literature search has been carried out however, to identify the daylighting designs available in the today, as documented by many researchers which include Freewan [29], Jeong & Kim [30] and Greenup & Edmonds [31]. The day lighting tools and devices from literature are: Light Pipes, Light Rods, Light shelves, Louvers, Laser Cut Panels (LCP), Prismatic Panels, Light-guiding Shade (LGS), and Holographic Optical Elements (HOE). This research will focus on one major designs or technologies which is the light pipe.

## 2.3 Shopping Malls and Daylight

The Definition of shopping mall differs from places and circumstances. The general idea behind a shopping mall is a collection of different commercial activities taking place in one entity. The encyclopaedia Britannica [32] defines a shopping mall as “a collection of independent retail stores, services, and a parking area conceived, constructed, and maintained by a management firm as a unit. Shopping malls may also contain restaurants, banks, theatres, professional offices, service stations, and other establishments”. The Oxford Advanced Learner’s Dictionary defines shopping mall as “a large group of shops or stores built together under one roof and closed to traffic”. The Wikipedia encyclopaedia [33] defines a shopping mall as “a building or set of buildings that contain a variety of retail units, with interconnecting walkways enabling visitors to easily walk form unit to unit”. The Microsoft Encarta [34] defines shopping malls as “collection of retail businesses in a building or set of buildings under one ownership or management”.

Cyril, [35] defines a shopping mall as “A shopping centre enclosed within a large structure; often two or three stories high, often designed around a central atrium; may have numerous stores, as well as entertainment facilities such as movie theatres, fast-food outlets, restaurants, and public areas.”

For the purpose of this research the definition below shall be adopted: A shopping mall is defined as a fully enclosed collection of independent retail units and services in a climate-controlled environment, with covered pedestrian walkways and restricting vehicular access at its periphery, run and by one management.

### 2.3.1 General evaluation of Daylight in shopping malls

In today's society, most people spend a considerable amount of their time in shopping centre buildings. As observed by Stevens and Rea [36] “humans have moved from a terrestrial environment with dark nights and bright broad-spectrum days to a modern built environment with relatively dim. Limited-spectrum days and nights”. One consequence of this move that has not yet been fully appreciated is the effect on people's health and well-being. In addition, the operation of these buildings consumes large quantities of electricity and therefore fossil fuels for illumination and air-conditioning [36].

One of the principles of sustainable architecture is to increase the use of natural light for illumination, particularly in shopping centre buildings, to reduce the dependence on electricity for illumination, thereby reducing the overall building energy consumption. Additional effects of using daylighting for illumination are improving the health and productivity of occupants of buildings, as well as enhancing the aesthetic qualities of buildings [36].

Numerous researches have been done to utilize and harvest the energy saving benefits of daylighting. Day-lit commercial buildings are capable of reducing capital costs by cutting on glazing and minimizing solar heat gain by carefully designing windows [37].The author point out that natural lighting also plays a very important role in increasing face value and adding aesthetic appeal. “Natural lighting would make the building more attractive resulting to a more valuable building with more valuable renting space. In other words, the value of a building can be increased with the use of natural lighting.” [37].

The increase of research in daylighting strategies in commercial buildings also help in producing new and cheaper methods of daylighting in buildings. This is another contributing factor on the rise of researches in energy conservation through daylighting. Northen [38] in his research on daylighting applications in commercial buildings found that lighting of buildings can be optimized and cooling loads can be minimized by using daylighting through proper design of the building envelope.

Another way to test the link between daylight and shopping centre is to find out the effect of daylight to enhance indoor environment quality that will result to attract more customers and this idea agreed by research which has been done by the Heschong Mahone Group in California on the effects of daylight towards retail sales they found that "daylighting was found to boost sales by an average of 40 percent with a 99 percent degree of statistical certainty" [39].

Research has shown that naturally lit buildings are more comfortable for human occupation and produce positive influence on operating income, resulting in increases in asset valuation [40]. Daylighting has been underscored as a factor in attracting and retaining workers. Daylight benefits such as increased workplace productivity and safety of building occupants. The pleasant environment created by natural light decreases stress levels for commercial office workers. Productivity increases with the improved health of workers, and with better productivity comes financial benefits for employers [36]. The same can be valid for shopping centre workers.

### 2.3.2 Problematic Spaces in shopping malls According to Daylight

Multi-storey shopping mall can be easily described as a building having more than one storey (excluding car parking and service) and shops are arranged at these levels and connected horizontally and vertically by various circulation areas. Multi-storey buildings are the most common mall type. There are different surface geometries, circulation plans and galleries in these buildings [41].

Previous research on Ankara malls by Al-Jubouri [41], showed that interior spaces of the enclosed shopping mall examined according to daylight abundance had major problematic spaces. By rendering the multi-storey shopping malls in Ankara It was found that the most problematic interior spaces in terms of using daylight as below:

a. Circulation around Single Gallery
b. Circulation around Multi Gallery
c. Under Ground Spaces
d. Shop Spaces

## 2.4 Climate Based Daylight Modelling (CBDM)

Climate-based daylight modelling is the prediction of various radiant or luminous quantities (e.g. irradiance, illuminance, radiance and luminance) using sun and sky conditions that are derived from standard meteorological datasets. Whilst it hardly needs remarking that daylight is inherently climate-dependent and time varying, the accepted evaluation method, called the daylight factor, makes no account of this everyday reality [42].

Climate-based daylight modelling have been described in various publications since the first reports around the turn of the millennium [42]. However, it is fair to say that acceptance has been slow amongst significant sections of the daylighting community, both practitioners and researchers [42].

The ability to undertake a year-round assessment of day lighting using site-specific climatic datasets and orientation of the building into consideration makes this the methodology of choice for this research. It takes into consideration direct sunlight, diffused daylight and the inter-reflected daylight within a space into consideration when simulating. With access to computer hardware and software at affordable costs, this methodology will counter the limitations of the daylight factor and the single point in time methods [43].

Using CBDM in place of daylight factors provides far greater detail about light distribution and intensity which allows the building design to be adjusted to maximize the use of sunlight and daylight. Annual weather data are used to calculate lux levels and targets can be set which are relative to user needs [44].

Derived from CBDM concept, a set of daylight specific performance indicators have been put forward by the proponents of this concept. These indicators have the ability to quantify and qualify day lighting in climate region, taking into consideration the location of the building and orientation inclusive of most climate peculiarities [43]. They include:

### 2.4.1 Performance Indicators

#### 2.4.1.1 Daylight Autonomy (DA)

This at a specified work plane location is defined as the percentage of the year when a minimum target illuminance for the day lit space is met by daylight alone. In mathematical terms, daylight autonomy is the percentage of annual work hours during which all or part of a building's lighting needs can be met through daylighting alone [45].

In general, a Daylight Autonomy threshold of 60% of the work plane illuminance (500 lux) that meets the recommended illuminance requirement is considered good day lighting, for shopping malls halls [46]. For values below the prescribed minimum illuminance, a modified version of the above metric known as continuous Daylight Autonomy (DAcon) allocates credit for partial daylight that does not meet the target illuminance [47] [48]. DA shows how well daylight penetrates into a space with appropriate display of the distribution pattern. In the absence of an upper limit on the allowed illuminance levels (until it meets the DAmax, which is ten times the benchmarked space illuminance level), poorly performing spaces with direct sunlight which is below the DAmax could do quite well with this metric. The DAmax of a factor of ten times the recommended illuminance is not backed by actual research, but is intuitive [48, 47].

#### 2.4.1.2 Useful Daylight Illuminance (UDI)

UDI is defined as the annual occurrence of illuminance across the work-plane that is within a range considered "useful" by occupants 100 to 2000 lux [44]. They decided to base the criteria on the useful daylight illuminance (UDI) metric. The useful daylight illuminance approach is founded on occupant responses to daylight levels, as reported in several studies [49]. It calculates the percentage of total number of occupied hours that 'useful' daylight enters a space at a selected point on the work plane [43]. It is the provision of ambient light at the work plane at illuminance levels is subdivided into:

a. UDI<100 represents illumination less than 100 lux.
b. UDI 100-2000 represents useful daylight
c. UDI>2000 represents an excess supply of daylight

Thus, only three metrics are used to characterize the hourly-varying daylight illuminances for an entire year at each of the calculation points.

#### 2.4.1.3 Simplified daylight glare probability (DGPs)

A major departure of DGP relative to other metrics summarized in this paper is that glare sources are determined by comparing areas of bright luminance against the total vertical eye illuminance for a viewing hemisphere of 2π sr. Therefore, DGP can evaluate direct sunlight falling on a work plane as a glare source while at the same time a dim visible sky might not be perceived as such. Specular reflections can also be seen as glare sources A glare probability >.45 corresponds to intolerable glare an estimated 45 percent of people would feel discomfort in such a lighting situation, while a value <.3 is considered imperceptible [50].

#### 2.4.1.4 Spatial Daylight Autonomy (sDA)

It is a single quantitative value for a space unlike the multiple values obtained in the Daylight Autonomy (DA) scheme. It has been put forward quite recently in the IESNA publication IES LM-83 [51]. It identified two levels for acceptability of performance: 'Preferred' and 'Nominally Accepted'. The 'Preferred' level is defined as a space with sufficiency of ambient daylight to meet or exceed 75% of sDA300, 50%, being the analysis points on the horizontal surface that meet or exceed 300 lux for 50% of the analysis period from 8am to 6pm. The 'Nominally Accepted' is defined as a space with sufficiency of ambient daylight for at least 55% of sDA300, 50%, being the analysis points on the horizontal surface that meet or exceed 300 lux for 50% of the analysis period from 8am to 6pm. This concept provides a single number for a space, more like the daylight factor (DF). It has already been experimentally verified to predict occupant satisfaction using a study of 61 different spaces by the authors [51]. On the other hand, the performance metric for all types of spaces are the same- be it a classroom, office or a shopping mall, which may highly be unlikely due to peculiarities of the different working environments. Being a relatively new concept, preconfigured tools for calculations are not available at present. Simplified daylight glare probability DGPs [52].

### 2.4.2 Performance Indicators for Quality

#### 2.4.2.1 Proposed Daylight Autonomy Uniformity Index (DAui).

Uniformity has often been expressed in terms of a ratio of two quantities, maximum to minimum, maximum to average and average to minimum illuminance over a work plane [53]. Uniformity in day lighting could also be taken to be the distribution of daylight across the work plane at an assumed height. A daylight autonomy uniformity index (DAui) was proposed by Salisu, [43] to assess uniformity in the spaces that have fenestrations on opposite facades.

This will be calculated as a ratio of maximum measured daylight autonomy to the average daylight autonomy of the assessed space and the closer this value is to '1'; the more the daylight is uniformly distributed in the space [43].

#### 2.4.2.2 Useful Daylight Illuminance greater than 2000 lux (UDI>2000)

Using this indicator, which is one of the three bins of the Useful Daylight Illuminance concept of CBDM, an assessment of the probability of solar gains and glare can be undertaken. Using a threshold of 2000 lux, these two qualities of daylighting in a space can be assessed using simpler and less complicated methods of 'flagging' of potential areas of thermal and visual discomfort. This threshold was arrived at after extensive survey on occupants in day lit office environments under a wide range of illumination conditions [54]. Though it will be ideal to achieve a 5% value or less for this performance indicator, the SLL (Society of Light and Lighting, SLL, 2011) has come up with the following criteria:

a. For new buildings, the combined value of the UDI<100 and UDI>2000 on a horizontal work plane should not exceed 20% of the assessed time of the activity period.
b. For refurbished buildings, the UDI>2000 should not exceed 20% of the assessed time.
c. The Annual Sunlight Exposure (ASE)

This is a relatively new performance indicator put forward recently by the IESNA. This is a metric that describes the potential for visual discomfort by calculating the number of hours in a year that direct sun is incident on a surface. A threshold of 1000 lux for 250 hours in a year was selected based on user surveys as an indicator for tolerance level that can be used to compare spaces [51]. This metric can flag potential issues of thermal discomfort and glare caused by direct sunlight from the sky, but does not provide for glare from specular reflections or veiling glare. Being a relatively new metric, preconfigured tools for calculations are not available at present [43].

## 3. Methodology

A qualitative research approach was used using a computer simulation with climate-based data. A base case model of a shopping mall was created to determine the effect of change in light pipe diameter for each of the samples, investigating Daylight Autonomy (DA), Useful Daylight Illuminance (UDI 100>2000) and Useful Daylight Illuminance (UDI>2000). Also, Illuminance Sufficiency, Probability of Glare and Thermal loads, and Daylight Distribution are investigated. Interpretation of Data generated from simulations using benchmark values for daylighting metrics of DA, UDI and DA Uniformity Index where available and the results are presented using charts, graphs and tables.

## 3.1 Dependent and Independent variables

Daylight specific performance indicators have been put forward by the proponents of this concept. These indicators have the ability to quantify and qualify day lighting in climate region, taking into consideration the location of the building and orientation inclusive of most climate peculiarities. The dependent variable is the light bulb diameter while the independent variables are Daylight autonomy (DA), continuous Daylight autonomy and daylight Illuminance.

## 3.2 Simulation software and modelling process

The parameters were input into the Ecotect®, Radiance and Daysim® software so as to compare and validate results. The room was modelled in Revit® architecture Design software as seen in Figure 1 and 2.

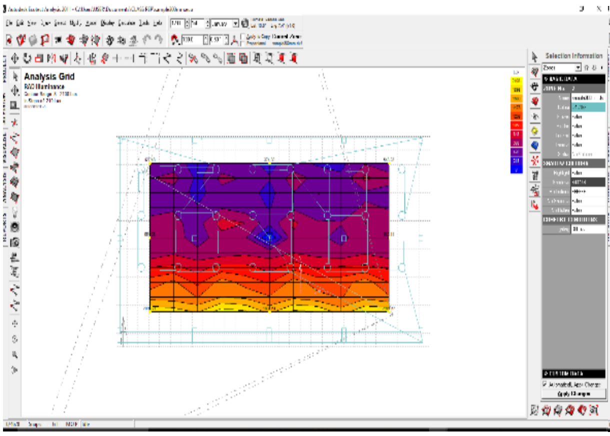

Figure 1: Applying material

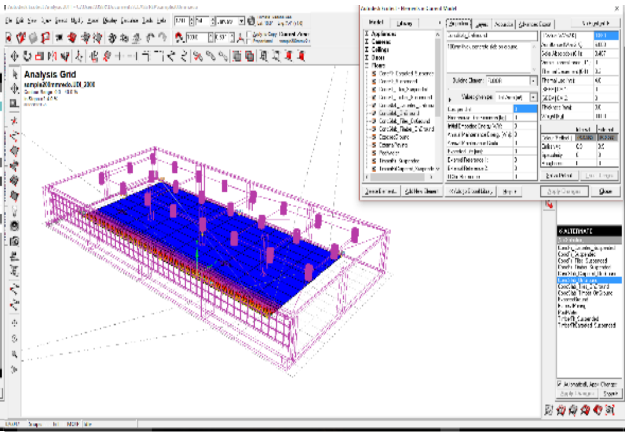

Figure 2: Visualizing the result

The base models are also presented showing the positions of the light pipes and their different diameters in the software interface showing the elevations and the plans. The following plates shows the plans and interior elevations of the base models showing the arrangements and placements of the light pipes and the results recorded and shown using charts.

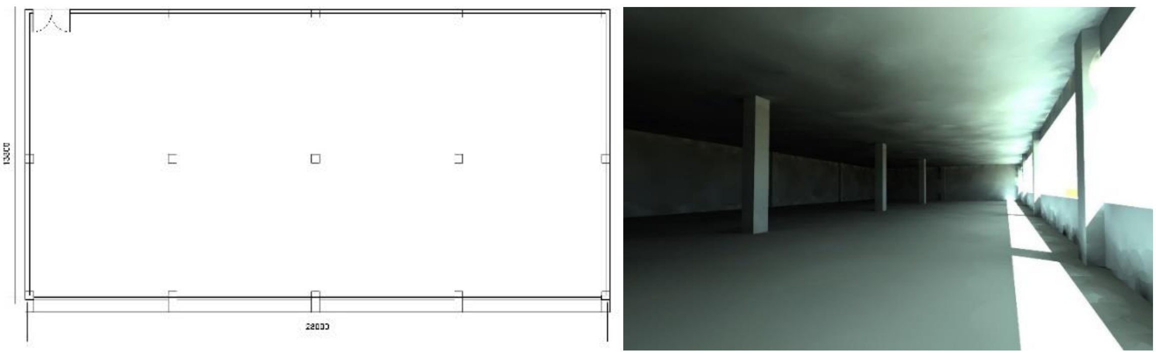

Plate I: Sample Base Model without Light Pipe.

Plate I show the floor plan of the base model without any light pipes while plate II shows the plan with light pipes of 150mm diameter light pipes. The results recorded and presented.

Plate II: Model with 150mm diameter Light Pipe

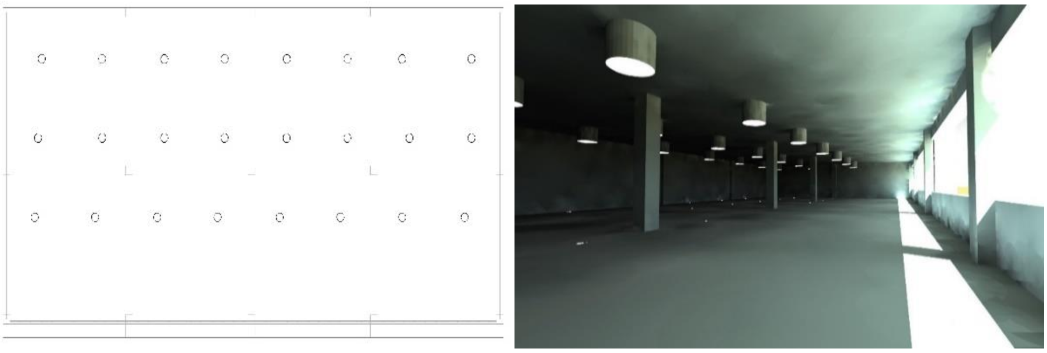

Plate III: Model with 300mm diameter Light Pipe

Plate IV: Model with 450mm diameter Light Pipe

Plate III shows the base model with 300mm diameter light pipes and results recorded and presented for discussion. As seen in plate IV, the light pipes diameter was adjusted to 450mm and the results documented and presented for discussion. As can be seen from the plates I, II, III and IV above, the over daylight was calculated and the best light pipe diameter was calculated.

## 4. Results and Discussion

Results from the computer simulation conducted and reported in charts. The luminance level of various light pipes diameter is presented in Figure 3.

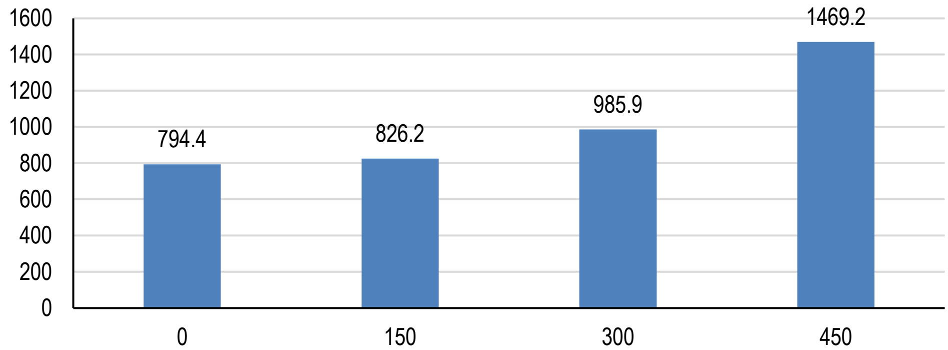


Figure 3: Average luminance levels of varying light pipe diameter

Figure 3 shows the result of the simulation with varying diameter of light pipes. The sensor points 1, 4 and 7 giving the highest readings are areas closest to the window giving too high lux levels and possibilities of glare occurrence. The area of concern in this simulation are areas away from the reach of the daylight from the window. Points 3, 6 and 9 reveals the amount of light provided into areas unaffected by the light pipes. From this table we can clearly see that light pipe 300 mm diameter meets up with the 500lux specification required for the showing mall without the accompany effects of glare and overheating. Figure 4 shows the average daylight autonomy of the base model with different light pipes diameters.

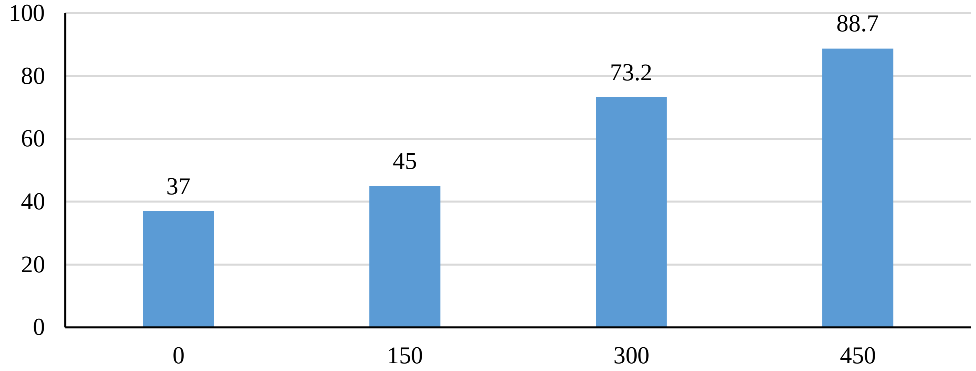


Figure 0: Average daylight autonomy of simulated space

Figure 4 illustrates a relationship between a light pipe diameter and average daylight autonomy showing a 52% increase in Daylight autonomy from no light pipe at 37% being the lowest to 450 mm diameter light pipe at 88.7% as the highest. The table also shows us that light pipe with 300mm diameter achieves the closest range of 60% DA value throughout the year as optimum value. Therefore, we say there was an increase of 36% in Daylight Autonomy from no light pipe to optimum light pipe diameter at 300mm. Figure 5 shows the useful Daylight illuminance greater than 100 average for the simulated space.

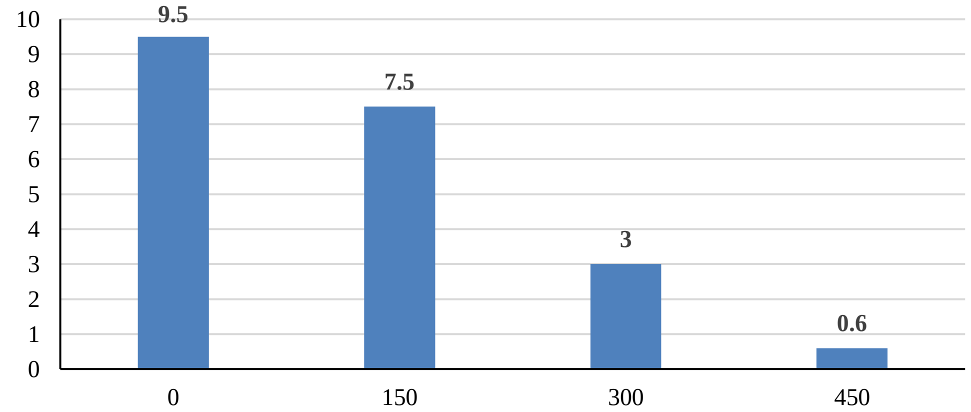


Figure 5: Average useful daylight illuminance >100 for simulated space

Figure 5, illustrates a relationship between a light pipe diameter and Useful Daylight Illuminance < 2000 showing a 15% increase from no light pipe at 10% being the lowest to 15% at optimum 300mm diameter light pipe. A sharp increase of 29% is achieved from a 300mm diameter light pipe to that of 450mm. This region of illuminance is responsible for an assessment of the probability of solar gains and glare. Using a threshold of 2000 lux daylighting in a space can be used to assess potential areas of thermal and visual discomfort. According to the British Society of Light and Lighting, for new buildings, the combined value of the UDI<100 and UDI>2000 on a horizontal work plane should not exceed 20% of the assessed time of the activity period.

From the simulated result in figure 5, it is clear to infer that light pipe diameter 300mm meets these requirements of not exceeding a 20% UDI>2000 throughout the year making it the optimum light pipe diameter size. The simulation result shows the following:

a. Adequate DA values of 60% over the sensors on the work plane are achieved in the shopping mall with light pipe diameter of 300mm.

b. Change in light pipe diameter has a major influence on the performance indicators. This shows by;
   i. An increase of 36% in Daylight Autonomy from no light pipe to optimum light pipe diameter at 300mm.
   ii. A decrease of 6% in average useful Daylight Illuminance > 100 from no light pipe at 9.5% being the highest to 3% as the optimum light pipe diameter at 300mm.
   iii. An increase of 4.3% in average useful Daylight Illuminance 100-2000 lux from no light pipe at 77.3% to 81.4% at 300mm diameter light pipe.
   iv. Adequate Useful Daylight Illuminance > 2000 values of 15% over the sensors on the work plane are noticed in the shopping mall for light pipe diameter of 300mm.

Firstly, findings showed that the quantity of daylighting was affected by a change in Diameter of light pipe, with a 85% increase in average lux levels from 794.4 lux at no light pipes to the 1469.2 lux at 450mm diameter light pipe, a 36%

increase in Daylight autonomy from 37% at no light pipe to 73.2% at 300mm diameter light pipe and a 6% decrease in average useful Daylight Illuminance > 100 from 9.5% at no light pipe to 3% at 300mm diameter light pipe.

Finally, 300mm was found to be the optimum diameter of light pipe for adequate lighting of shopping mall by achieving adequate DA values above 60% and remaining within Useful Daylight Illuminance < 2000 at 15%.

## 5. Conclusion

In conclusion, the 300 mm diameter of light pipe was found to be the optimum diameter for adequate lighting of shopping malls thereby achieving adequate DA values above 60% and remaining within Useful Daylight Illuminance > 2000 at 15%.

## Recommendations

After a thorough study, the following recommendations were made;

a. Light pipes should have a minimum diameter of 300mm to ensure maximum levels of daylighting while minimizing risk of glare.
b. Light simulation should be carried out for every design using appropriate methodology to enhance visual comfort reducing energy consumption in the building.

## References


[1] Tregenza, P., & Wilson, M. (2013). *Daylighting: architecture and lighting design*. Routledge.

[2] Reinhart, C., (2006). Daylighting – light, form and people. *Energy and Buildings 38, 715-717.*

[3] Leslie, R. P., (2003). Capturing the Daylight Dividend in Buildings: Why and How? *Buildings and Environment. 38. 381-385.*

[4] Erlendsson, Ö., (2014). Daylight Optimization: A Parametric Study of Atrium Design. Early-Stage Design Guidelines of Atria for Optimization of Daylight Autonomy. *SE 100–44 Stockholm, Sweden: TRITA-IES.*

[5] Iliyasu, A. D., (2011). Proposed Shopping Mall, Millennium City, Kaduna. Integrating Shopping and Recreation Facilities. *Zaria: Ahmadu Bello University, Zaria.*

[6] Shao L., and Callow J. M., (2003). Daylighting performance of optical rods, *Solar Energy, 75, 439-445.*

[7] Yohannes, I. (2001). Characterising the performance of light-pipes in UK climates. *PhD Dissertation, University of Nottingham.*

[8] EREC (2001). Energy efficiency and renewable energy clearing house, *Merrifield, VA 21116 USA.* *http://www.eren.doe.gov/consumerinfo/refbriefs/tpgcc.html.*

[9] Cakir, A. & Cakir, G. (2000). Light and health in why humans need daylight at their workplace, *Ergonomic Institute – Berlin. Retrieved May 20, 2000, http://www.healthylight.de/day.html.*

[10] Deru, M., Blair, N., & Torcellini, P. (2005). *Procedure to measure indoor lighting energy performance* (No. NREL/TP-550-38602). National Renewable Energy Lab.(NREL), Golden, CO (United States).

[11] Phillips, D. (2004). *Daylighting: natural light in architecture*. Routledge.

[12] Baewon Koh, B., & Meyer, P. (2015). New innovation in daylighting design. *Innovative design. Innovative Design, Inc. Retrieved from* www.innovativedesign.net

[13] Helmut, K., (2004). Dynamic daylighting architecture: basics systems projects. *Basel, Switzerland: Birkhäuser. http://www.monodraught.com/daylight_products.html retrieved 21/12/2017.*

[14] Hasen, G. V., (2006). Innovative Daylighting systems for deep plan commercial buildings. *School of Design Queensland and University of technology*. Mendoza.

[15] Ander, G. D., (2014). U.S. Department of Energy Federal Energy Management Program (FEMP*). Retrieved may 12, 2016, from National Institute of Building Sciences:* http://www.wbdg.org/resources/daylighting.php.

[16] Tukur, R. B., (2013). Harnessing daylight potentials as a tool for visual and thermal comfort in residential buildings. *Published PhD Thesis. University of Nottingham:*

[17] Onuwe, J. O., Goshi S. K., and Alonge, D. O., (2015). Assessment of Day Light Design Considerations in Kogi State Museum. IOSR-*Journal of Environmental Science, Toxicology and Food Technology (IOSR-JESTFT),* 48, 75-86

[18] Naseri, O. (2014). Reconsideration of Opening Design in the Integration of Natural Light into Interior Space. *Gazimağusa: Eastern Mediterranean University; North Cyprus.*

[19] Jinia, M. A., Trisha, S. H., & Mahmood, T. (2015). Performance of fixed shading devices on daylight penetration in the tropical city like Dhaka. *American Journal of Energy Science*, *2*(3), 21-27.

[20] Prowler, D., & Prowler, D. (2008). Sun control and shading devices. *Whole Building Design Guide*.

[21] Green Building Manual, N. J. (2011). Building Orientation. *New Commercial updated*.

[22] US DOE. (2014). Massing & Orientation for Daylighting. *Orientation daylighting, US department of Environment,* Retrieved from: *http://auworkshop.autodesk.com/library/building-science/massing*

[23] Ander, G. D., (2014). Daylighting. *Southern California: U.S. Department of Energy Federal Energy Management Program (FEMP*), California.

[24] Reinhart, C. F., & Wienold, J. (2011). The daylighting dashboard–A simulation-based design analysis for daylit spaces. *Building and environment*, *46*(2), 386-396.

[25] Nair, M., Ramamurthy, K. and Ganesan, A., (2014). Classification of indoor daylight enhancement systems. *Lighting Research and Technology*, 46, 245-267.

[26] Allen, M., Wolfgang, S., Montgomery, C., Lee, A., Murray, B., and Rosenthal, S., (2008). Elements of Daylighting. *Norfolk: Clark Nexsen Architecture and Engineering.*

[27] Egan, M. D. (2002). Architectural Lighting, McGraw-Hill, New York.

[28] Roaf, S., Horsley, A., Gupta, R. (2004). Closing the loop: Benchmarks for sustainable buildings. *Edited by Melanie Thompson. RIBA Enterprises Ltd, London. 309-316.*

[29] Freewan, A. A. (2007). Optimising the performance of innovative daylighting systems by integrating with ceiling geometrics. *PhD Dissertation, University of Nottingham.*

[30] Jeong T.K and Kim. G. (2009). Overview and new developments in optical daylighting systems for building a healthy indoor environment. *Building and Environment 45, 256-269.*

[31] Greenup, P. J. & Edmonds, I. R. (2004) Test room measurement and computer simulations of the micro-light guiding shade daylight redirecting device. *Solar Energy, 76, 99-109.*

[32] Encyclopaedia Britannica (2020). Definition of shopping mall. Retrieved from https://www.britannica.com/dictionary/shopping-mall

[33] Wikipedia encyclopaedia (2020). Shopping Mall. Retrieved from https://en.wikipedia.org/wiki/Shopping_mall

[34] Microsoft Encarta (2008). Definition of shopping mall. Microsoft/Encartadictionary

[35] Cyril, M. H. (E.d). (2006). Dictionary of Architecture and construction, *McGraw-Hill, New York, pp 884 - 509.*

[36] Stevens, R. G. and Rea. M. S., (2001) Light in the built environment: potential role of Circassian disruption in endocrine disruption and breast cancer. *Cancer Causes and control. CCC, 12, 279-287.*

[37] Loveland, J. (2002). Daylighting and Sustainability. *Environmental Design & Construction*, *5*(5), 28-32.

[38] Northen, R. I. and Haskoll, M. (1977). Shopping Centres: A Developer's Guide to Planning and Design. *Centre for Advanced land Use Studies, College of Estate Management, UK.*

[39] Claridge, D. E. and Haberl, J. S., (1994). Energy Retrofits Can Cut Use and Costs. *Mechanical Engineering, 116(8), Texas, USA.*

[40] Katz, D., (2005). Daylight Harvesting Technologies. *Energy Engineering. Volume 102, 40-51.*

[41] Al-Jubouri, O. H., (2012, May). Importance of Daylight as a Component of Sustainability in Shopping Mall Example. Ankara, Turkey: *Çankaya Üniversitesi.*

[42] Mardaljevic, J., (2006). Examples of Climate-Based Daylight Modelling. *CIBSE National Conference 2006: Engineering the Future 21-22 March 2006 (p. 2). London: CIBSE National Conference.*

[43] Salisu, A. S., (2015). Optimising Fenestration for Daylight Provision in the Architecture of Secondary Schools in Nigeria Using Climate-Based Daylight Modelling, Ahmadu Bello University, Zaria, Zaria.

[44] Moreno, M. B. P., & Labarca, C. Y. (2015). Methodology for assessing daylighting design strategies in classroom with a climate-based method. *Sustainability*, *7*(1), 880.

[45] Manic, M., Amarasinghe, K., Rodriguez-Andina, J. J., & Rieger, C. (2016). Intelligent buildings of the future: Cyberaware, deep learning powered, and human interacting. *IEEE Industrial Electronics Magazine*, *10*(4), 32-49.

[46] Wrixon, G. T., Rooney, A. M. E., & Palz, W. (2012). *Renewable energy-2000*. Springer Science & Business Media.

[47] Reinhart, C., (2006) Daylighting – light, form and people. *Energy and Buildings 38, 715-717.*

[48] Rogers, Z., & Goldman, D. (2019). Daylighting metric development using daylight autonomy calculations in the sensor placement optimization tool, Boulder, Colorado, USA: Architectural Energy Corporation, 2006.

[49] Mardeljevic, j., Brembilla, E. and Drosou, N., (2016). Real-world validation of climate-based daylight metrics: mission impossible. Presented at: *CIBSE Technical Symposium 2016, 14th-15th April 2016, HeriotWatt University, pp. 1-12. Edinburgh: Chartered Institute of Building Services Engineers (CIBSE).*

[50] Jakubiec, J. A. and Reinhart, C. F., (2012). The 'adaptive zone' a concept for assessing discomfort glare throughout daylit spaces. *Lighting Research and Technology, 44(2), 149-170.*

[51] Illuminating Engineering Society (IES) Daylight Metrics Committee, (2012). Approved method: IES spatial daylight autonomy (sDA) and annual sunlight exposure (ASE). *Illuminating Engineering Society of North America, New York.*

[52] Illuminating Engineering Society of North America (2000). The IESNA lighting handbook, reference & application. New York: IESNA. Innovative design. (2004). guide for daylighting schools. *Daylight dividends: lighting research centre rensselaer Polytechnic Institute, New York.*

[53] Nabil, A., & Mardaljevic, J. (2005). Useful daylight illuminance: a new paradigm for assessing daylight in buildings. *Lighting Research & Technology*, *37*(1), 41-57.

[54] Society of Light and Lighting (SLL), (2011). *SLL lighting guide 5: Lighting for education.* London: Chartered Institution of Building Services Engineers (CIBSE).