Daylight Optimization to Leverage the Reduction in Energy Demand for Artificial Lighting in Indoor Sports Arena

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ABSTRACT

Exploratory surveys on existing indoor sports halls reveal that their designs mostly neglect daylight to rely totally or partially on artificial light, forfeiting all the benefits of natural light. Natural lighting in indoor spaces has proven to be of several immense benefits to users and owners of these spaces. Several factors have been identified that affect the quality and quantity of daylight of an enclosed space, the most significant of them all is a window to floor ratio. The study is aimed at optimizing effective daylight in indoor sports halls by evaluating daylighting provision in some existing indoor sports halls in Nigeria, taking into consideration illuminance levels and uniformity indices. Descriptive analysis was carried out, which formed the basis upon which a Climatic Based Daylight Model was developed. Three distinct daylight schemes were modelled and analyzed, and the first scheme (combination of sidelight and top-light) has successfully and optimally harnessed daylight in an indoor sport hall. The scheme attained the minimum requirements for illuminance, vertical illuminance and uniformity index, which can be replicated in environments of similar climate.

Keywords: daylight, illuminance, uniformity index, indoor sports hall

1. INTRODUCTION

Lighting is one of the most significant elements for visual comfort, especially when a right balanced is achieved between artificial and natural lighting. Natural lighting, also known as daylight, in indoor spaces has proven to be of several benefits (Edwards & Torcellini, 2002). Daylight plays a crucial role in determining participants' and viewers' visual comfort in indoor environments (Veugelers, 2017). It is an essential element that aids people in appreciating the internal environment, save energy and respond positively to various tasks (Ishac & Nadim, 2016). It is noteworthy that daylight is contextually free, especially when effectively harnessed. However, these benefits are not harnessed to the fullest due to the total or partial reliance of most indoor environments on artificial light day and night (Michael, 2021). It is also noteworthy that natural light cannot totally be a substitute to artificial light for visual comfort in any large indoor environment, such as a sports facility (Executive & Final, 2021).

Artificial lighting, on the other hand, cannot be obtained free of charge and without negative impact, it produces a significant amount of carbon dioxide which contributes to global warming (Wong, 2017), it accounts for up to 40% of yearly building energy consumption and consumes 20% to 30% of overall energy use in commercial buildings (Astrich et al., 2009). Moreover, to provide even illumination free from glare in an enclosed space, significant amount of electric lighting is needed, otherwise a lot of dark areas would be prevalent.

Apart from the pleasure driven from it, sporting activities complement a vital part of human physical exercise. Sports form greater part of physical exercises and regardless of where they take place, the indoor comfort required for those activities mainly include thermal and visual comfort (Executive & Final, 2021). Okotete (2016) reported that research conducted by a medical practitioner and psychologists shows how important daylight is to the physical and mental wellbeing of an individual. The government through health care awareness programs has been encouraging people to increase more physical activities through exercises to be healthy and physically fit. As a result, small scale sports facilities are springing up to accommodate mostly outdoor sports, however indoor sports are equally needed to compliment the former.

Many sports are played in indoor sporting facilities, and the lighting requirements differ accordingly (EN 12193:2007). These requirements differ depending on the activity to be performed; EN 12193 (2007) states that lighting between 200 and 750 lux is adequate for all indoor sports. However, light is needed in proportion to the size and speed of balls being played. Most ball sports, for example, require 200 lux, while squash and table tennis require 300 lux (EN 12193, 2007). Due to the adherence to this standard and other factors, most indoor sports facilities do not apply natural light in their architecture (Münch et al., 2020). Exploratory surveys undertaken by Wong (2017) on existing indoor sports complexes reveal that their designs mostly neglect daylight to rely totally on artificial light to achieve visual comfort during the day, forfeiting all the benefits of natural light.

The consequences of total reliance on artificial light have resulted in the application and the utilization of more energy, during the day and night. However, power (electrical energy) has been an issue in Nigeria, despite efforts to increase the quantity of power generated through the privatization of the Power Holding Company of Nigeria (PHCN), Nigeria's power supply remains epileptic, with approximately 75% of the population are living without electricity (Okotete, 2016). As a mitigation measures, optimizing daylighting in our buildings, will certainly save us significant number of resources, increase levels of economic activities and raise the citizens' health levels. The aim of the study therefore, is to determine the possibility of complimenting artificial light with daylight to achieve optimum lighting in large halls.

2. LITERATURE REVIEW

Different countries have different climatic conditions, different sky and lighting conditions, so designers must be able to work with whatever light is available and design buildings that suit each climatic conditions (Edwards & Torcellini, 2002). Understanding the composition of light, how light is quantified, light characteristics and how light affects our daily lives form the foundation of optimizing daylight in our built environment (Alhazzaa, 2021).

2.1. Light

The portion of the electromagnetic spectrum between 380 and 780 nanometers (nm), as depicted in Figure 1, that evokes a visual reaction in humans is referred to as light, and it is the only physical quantity described entirely in terms of the human sensory mechanism (Thayer et al., 2020). The pattern of light and dark events on the retinae also provides timing signals that warn and synchronize the circadian processes of human and numerous other species, ranging from bacteria, plants and fungi to insects, amphibians and mammals.

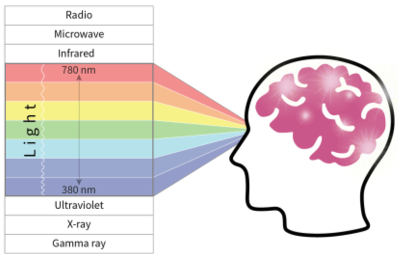

Figure 1: Light Waves Visible to the Human Eye (Source: Thayer et al., 2020)

Before the second half of the twentieth century, when artificial illumination was invented, daylighting reigned supreme in the art of architecture. Electrical illumination provided a cost-effective and efficient way to build spaces without having to worry about the location of daylight sources (Business, 2013). In the latter half of the twentieth century, an energy shortage forced designers to rethink the potential for daylighting. In large commercial buildings the consumption of electrical energy due to extensive use of air conditioning is more during the sunny summer afternoons. Proper utilization of daylight can aid in reducing as much as 50% of electrical light energy (Lencher, 2015).

2.1.1 Characteristics of Daylight

Clear sunlight, light diffused from an overcast sky, fog or reflections from the ground or nearby buildings may all enter a building through windows or other fenestrations (Business, 2013). Figure 2 shows overcast sky, clear sky and cloudy sky that are the three types of sky conditions used to estimate illumination levels within a space (Lencher, 2015). The illuminance ranges of the overcast sky dome are usually 10,000 to 30,000 lux, ranging from winter to summer and clear sky is brighter than an overcast sky (Ander, 1995). Cloudy sky light condition, on the other hand varies from very high to quite low, it blocks the sky dome to a maximum of between 30 and 80 percent.

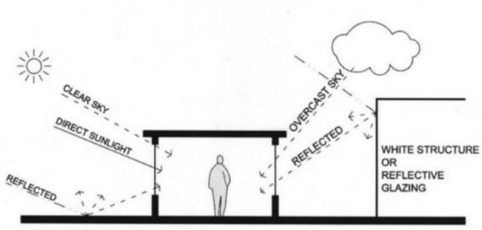

Figure 2: Sources of Daylight (Source: Ander, 1995)

2.2 Objectives of Daylighting

When designing a well day-lit space, there are several clear daylighting objectives to keep in mind, the opening positions and the variability of daylight quality are essential (Alhazzaa, 2021). According to Business (2013) the most critical aspects of daylighting to take into account when designing for daylight are the following:

1. Reduce direct glare of uncontrolled windows or skylights,
2. Prevent excessive brightness caused by a direct beam over a task area,
3. Daylight should be diffused by multiple reflections off the walls and ceilings,
4. Take advantage of aesthetic aspect of daylighting by using direct sunlight as a design element in non-critical task areas, and

The daylight should be taken deeper into the interior of the space.

2.3 Health Benefits of Daylight

Electromagnetic radiation has both adverse and positive effects on the human body. The negative effects can be both rapid; such as burning and slow; such as cancer and its growth. Direct sunlight on the skin can be beneficial, but there must be a balance between the effects of over-exposure and under-exposure to sunlight (Thayer et al., 2020). The optimal exposure to daylight for mental and physical wellbeing cannot be guaranteed solely by the architecture of a building, but the way a person lives is another factor. Accordingly, the fundamental needs are:

1. A 24-hour cycle of illumination that includes periods of darkness and of bright light,
2. Exposure to bright daylight during winter months,
3. The need of building users for a sense of contact with the outside world, and
4. Avoidance of glare that causes discomfort or reduces visibility of hazards.

The importance of each of these depends on the building type and the circumstances of the users.

2.4 Planning Elements for Daylight Use

Electromagnetic radiation has both adverse and positive effects on the human body. The negative effects can be both rapid; such as burning and slow; such as cancer and its growth. Direct sunlight on the skin can be beneficial, but there must be a balance between the effects of over-exposure and under-exposure to sunlight (Thayer et al., 2020)

2.5 Visual Comfort in Relation to Daylight

Regardless of the many advantages of sufficient daylighting in a building, its absence results in other adverse conditions. Under-illumination, over-illumination and glare are the three main categories of negative conditions that an indoor environment experiences in a poorly designed daylight space (Pietrack, 2018). However, there are challenges in designing for effective daylighting. First, daylighting must be balanced against overheating due to solar gain, time of the day and seasonal variations. Second, it is only successful when the brightness from light sources is fully managed and direct glare avoided. Finally external view, as a critical component of effective daylight design must be considered (Ali, 2021).

2.6 Daylight Design

2.6.1 Sidelight method

This refers to daylight that comes primarily from the exterior walls' side, see Figure 3. The appropriate size of an aperture, its location in relation to the morphology of the interior space and the facade are the factors to consider when illuminating a space from one side. The recommended option for simultaneously optimizing energy performance and occupant comfort is moderately sized windows with fixed shading devices, therefore, excess daylight and heat gains tend to cause thermal and visual discomfort, hence facades with more than a 60% window-to-wall ratio should be avoided (Luster, 2017).

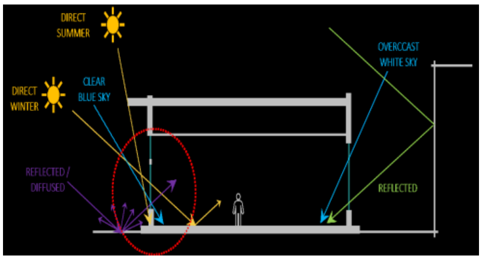

Figure 3: Side Lighting (Source: Luster, 2010)

2.6.2 Light Shelves Method

Horizontal shading and deflecting systems, such as light shelves, are forms of horizontal shading and redirecting devices. They have the huge influence on the elevation toward the south. Due to their nature, they reduce illumination near the window while pushing light deeper into the space (Luster, 2017). The depth is dictated by the shading requirements as well as the space and window geometry. The window above the light shelf is utilized to illuminate the space, while the bottom half of the window is utilized for ventilation, as shown in Figure 4.

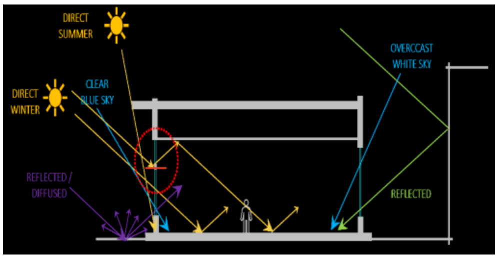

Figure 4: Light Shelves (Source: Luster, 2017)

2.6.3 Top Light Method

Top lighting comprises skylights, monitors, and clerestories (typically shown in Figure 5). The possibility for high-quality and high-quantity illumination over a large area is one of the benefits of top lighting. Unfortunately, there are several drawbacks to using top lighting. It is not a viable technique for high buildings, and because it does not meet the demand for view and orientation, it should therefore be used in conjunction with other strategies (Luster, 2017). All lighting from above, including top lighting, can create substantial glare and veiling reflections. The best way to avoid these reflections is to keep light sources out of the visual task's positions. Also, to block the light, use screens or banners, or reflect it off the ceiling.

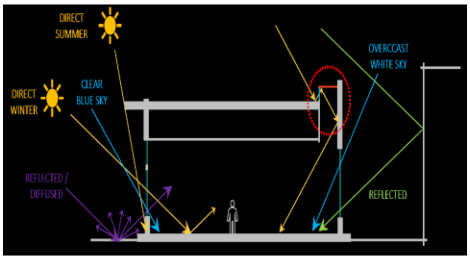

Figure 5: Top Lighting Strategy (Luster, 2017)

2.7 Climate-Based-Daylight-Modelling (CBDM)

The prediction of numerous radiant or luminous values (e.g., irradiance, illuminance, radiance, and luminance) using sun and sky conditions taken from conventional meteorological data is known as Climate-Based Daylight Modeling (CBDM) (Salisu, 2015). This has the potential to change how professionals and building designers think about and assess daylight, while also directing doubts of the traditional approach, which is based on the use of the Daylight Factor (DF) (Brembilla & Mardaljevic, 2019).

CBDM gives significantly more data on light distribution and intensity than DF, allowing the building design to be changed to maximize the utilization of daylight. Lux levels are calculated using annual weather data, and objectives may be established according to user requirements (Esquivias et al., 2016). A variety of tools may be used to conduct CBDM analysis, such as DIALux evo II and Relux. This technique was adopted for this research because it allows for a year-round assessment of day illumination employing site-specific meteorological variables and taking the building's orientation into account.

2.8 Daylight Autonomy

The percentage of yearly work hours during which all or part of a building's lighting demands may be satisfied solely by daylighting is known as Daylight Autonomy (DA) (Costanzo et al., 2018). In general, for most interior sports complexes, a DA threshold of 60% of 200 to 700 lux that satisfies the recommended illuminance required is considered adequate (Kensek & Suk, 2011). A modified variant of the above metric known as continuous Daylight Autonomy (DA_{con}) allocates credit for partial daylight that does not meet the goal (Esquivias et al., 2016).

2.9 Useful Daylight Illuminance (UDI)

The yearly incidence of illuminance across the work plane that is within a range considered beneficial by occupants – 100 to 3000 lux – is described as Useful Daylight Illuminance (UDI) (Mardaljevic, 2016). When daylight enters a location at a certain point on the work plane, the percentage of total occupied hours that are beneficial are estimated (Salisu, 2015). The provision of ambient light at the work plane at various illuminance levels is classified into three categories:

1. UDI<100 represents illumination less than 100 lux,
2. UDI 100-3000 represents useful daylight, and
3. UDI>3000 represents an excess supply of daylight.

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

2.10 Daylight Autonomy Uniformity Index (DA_{ui})

Over a work plane, uniformity is frequently expressed as a ratio of two sets of quantities: maximum to minimum, maximum to average, and average to minimum illuminance (IESNA, 2000). Salisu (2015) suggested the use of daylight autonomy uniformity index to analyze uniformity in areas with fenestrations on opposite faces (DA_{ui}), which is evaluated as a ratio of maximum daylight autonomy to average daylight autonomy of the evaluated space. The higher the value, the more evenly dispersed daylight is in the space (Moyano et al., 2020).

3. METHODOLOGY

Primary data for illumination of selected case studies of indoor sports halls in Northern Nigeria (Ahmadu Bello University, Zaria and Bayero University, Kano) were collected, modelled and analyzed to determine the optimum daylighting that meets the functional and visual performance needs of indoor sports complexes. Application of Climate-Based Daylight Modeling (CBDM) in architecture provides the required information of a space by making available detailed data to achieve an optimal level of illuminance, uniformity of illuminance and a decrease in the chances of direct and indirect glare, as seen from the literature. Therefore, CBDM method is chosen for this study because of its capacity to handle or deal with the continuous changing nature of Nigeria's tropical climate, as exemplified in Salisu (2015).

Similarly, simulations were carried out to assess the impacts of climate, orientation and the effects of fenestration type on the provision of daylighting in the said indoor sports halls. Discrete event simulation model was adopted, where observations were gathered at selected points at different times during the day. Models were developed based on the findings of the evaluation stage and various configurations of fenestrations identified which provided enough daylighting and decreased chances of glare occurrence.

The procedure and analysis adopted in this study are based on works conducted by Okotete (2016) and Mardeljevic, Brembilla & Drosou (2016). Both studies adopted the use of CBDM to asses long-term daylighting performance in terms of many metrics, such as UDI (useful daylight illuminance). The UDI is expressed as a percentage of the occupied time when a target range of illuminance at a point in a space is met. Four ranges were considered in this study; 0 – 100 lux (UDI-n, not sufficient); 100 – 300 lux (UDI-s, sufficient); 300 – 3000 lux (UDI-a, autonomous) and over 3000 lux (UDI-e, over illumination). The simulation results were obtained with 2-phase CBDM method known as daylight coefficient method, where course grids spacing of 20m were created over the area for a total of 20 points. Measurements were recorded at 1-minute resolution and later averaged over 10-minutes time step.

3.1 Evaluation of Existing Facilities

The experiment involves, among other metrics, taking physical illuminance of two purposively selected case studies; specifically, the indoor sports complexes in Bayero University, Kano (BUK) and Ahmadu Bello University, Zaria (ABU), for being within similar climatic zone. This was conducted to determine the actual daylighting needed to meet the functional requirements of visual performance in the halls. The application of DIALux evo II package was utilized to model and analyze illumination and metrics of visualization. A light meter was used in collecting the amount of daylight within the case studies for the analysis.

3.1.1 Case Study One, Bayero University, Kano (BUK) Indoor Sports Hall

The facility is made up of transitional rectangular shapes, giving the sporting area a perfect rectangle orientation with the longest sides facing west east direction. The form and orientation of the facility placed it at a disadvantaged position when it comes to harnessing daylight. The light comes in to the hall from high-level windows on the facility's East, West and North sides; the main glazing material utilized in the complex design is single-clear glazing with metal frame. In terms of both light and heat, single transparent glazing has the maximum solar transmittance. The complex has walling material with low thermal mass. From the literature, it was gathered that using construction materials with high thermal mass such as insulated brick cavity walls can reduce high heating and cooling energy requirements compared to one built with a low thermal mass. Plates 1, 2 and 3 show the external and internal views as well as Google earth map showing the location of BUK hall.

Plate 1: Bayero University, Kano (BUK) Indoor Sports Hall (Source: Author, 2022)

Plate 2: Location of BUK Indoor Sports Hall, (Source: Google earth-pro, 2022)

Plate 3: North Wall of Indoor Hall (Source: Author, 2022)

3.1.2 Case Study Two, Ahmadu Bello University, Zaria (ABU) Indoor Sports Hall

Ahmadu Bello University, Zaria (ABU) facility shown in Plates 4, 5 and 6 is made up of rectangular shapes, giving the sporting area a perfect rectangle orientation with the longest sides facing west-east direction. The form and orientation of the facility placed it at a disadvantaged position when it comes to harnessing daylight. The light comes in to the hall from high-level windows on the facility's East, West, and North sides; the main glazing material utilized in the complex design is single-clear glazing with metal frame. In terms of both light and heat, single transparent glazing has the maximum solar transmittance. The complex has walling material with low thermal mass. From the literature, it was gathered that using construction materials with high thermal mass such as insulated brick cavity walls can reduce high heating and cooling energy requirements compared to the one built with a low thermal mass.

Plate 4: ABU Zaria Indoor Sports Hall (source: Author, 2022)

Plate 5: Location of ABU Zaria Indoor Sports Hall (Google earth-pro, 2022)

Plate 6: Showing the Play Area (Source: Author, 2022)

3.2 Tools for Data Collection

The tools used for data acquisition from the case studies include:

1. Observation and measurements were adopted, where photographs were taken of relevant case studies to ascertain the features of natural lighting, the extent to which they were applied; whether strong, weak, or non-existent. Sketches were also made of some parts of the case studies, and
2. Modeling and simulation using DIALux evo II, based on EN 1838 2019-11. Its main features are: spot light on, indoor and outdoor light calculation, high quality visuals, light seeing ability, luminary partnership, beam object luminary, daylight calculation, calculation options and IFC import. Version: 5.11.0.63631, revised in October 2022. This supports window 11and runs on 64-bit system. Gives a wide selection range of

luminaries between 1 and 50 simultaneously. Has the ability to receive IFC files and has energy saving potential of all lighting projects.

3.3 Global Daylight Analysis Parameters

The following geographical parameters were adopted for the base cases in DIALux evo II:

1. Orientation: the north direction adopted was 30^0 North-East,
2. Building Type: large indoor sports hall,
3. Location: latitude 11.94788 and longitude 8.561454,
4. Glazing: Lamilux glazing properties were adopted for both top-light and side-light,
5. Fenestration: sidelight (0.9x1.8) m high level windows at a sill of 5m and top-light (1x1) m double glazed sky light,
6. Time Zone: (UTC +01:00), West Central Africa, and
7. Simulation Time: 12:00 pm.

The above items show the definition of all the geographical parameters that daylight is dependent on. The location was manually entered into the program using coordinates obtained from Google earth, all other parameters were automatically selected from the programme.

4. RESULTS AND DISCUSSION

In line with the focus of the research, two case studies were carried out on existing indoor sport complexes in Northern Nigeria, shown in Plates 1 through to 6 above. A two-line graph was used to compare the data obtained from the two case studies visually. The data was further examined using lighting measures such as uniformity ratio and variations in average measured illuminances to simulated illuminances. The entire process was broken down into the following stages:

1. Data collection,
2. Data evaluation and validation, and
3. Comparative evaluation and presentation of results.

Table 1 shows the magnitude of the measured luminance at 20 sensor points shown in Figure 6. The building parameters were utilized in developing a CBDM model that was analyzed to generate simulated luminance for every sensor point. The last column shows the difference between the measured and simulated luminance. The relationship between the values is graphically represented in the Figure 7.

From Figure 7 series 1, 2 and 3 represent measured lux, simulated lux and the difference between the two respectively. It can be observed that there is a harmonious flow between the measured and simulated luminance with negligible difference, the correlation between the two has validated the data collected, therefore the measurements became valid for further analysis.

Table 2 showed the magnitude of the measured luminance at the 20 sensor points shown in Figure 8, where series 1, 2 and 3 represent measured lux, simulated lux and the difference between the two respectively. The building parameters were utilized in developing a CBDM model that was analyzed to generate simulated luminance for every defined sensor point. The last column shows the difference between the measured and simulated luminance. The relationship between the values is graphically represented in Figure 9.

Figure 10 is derived from Table 3 and it can be observed that there is harmonious flow between the measured and simulated luminance with negligible difference, this correlation between the two has validated the data collected, therefore the measurements are valid for further analysis.

Table 1: Measured luminance, simulated luminance and Variance at 9:00 am

S/No.	Sensor Point	Measured (lux)	Simulated (lux)	Difference (lux)
1	G1	73	106.5	33.5
2	G2	83.3	175.3	92
3	G3	86.7	125.3	38.6
4	G4	81.3	76.3	-5
5	G5	112.3	149.7	37.4
6	G6	108.6	123.6	15
7	G7	112.6	145.7	33.1
8	G8	138.6	165.3	26.7
9	G9	158	135.9	-22.1
10	G10	97.3	63.9	-33.4
11	G11	182.6	205.3	22.7
12	G12	356	403.4	47.4
13	G13	337.3	378.4	41.1
14	G14	314	389.7	75.7
15	G15	224	235.3	11.3
16	G16	307.6	325.3	17.7
17	G17	451	473.9	22.9
18	G18	400.33	425.7	25.37
19	G19	409.66	486.3	76.64
20	G20	227.3	275.6	48.3

Average measured illuminance = 213.0745 lux
Average simulated illuminance = 243.3200 lux

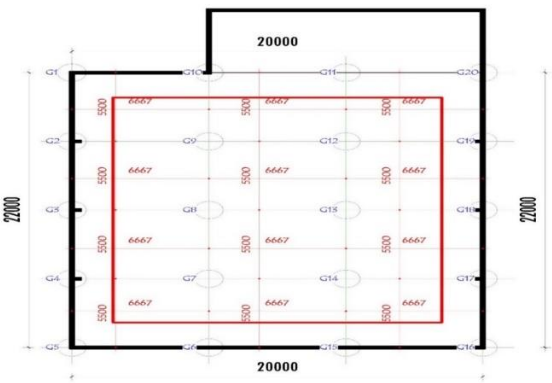

Figure 6: BUK Grid Sensor Points for Data Collection (Source: Author, 2022)

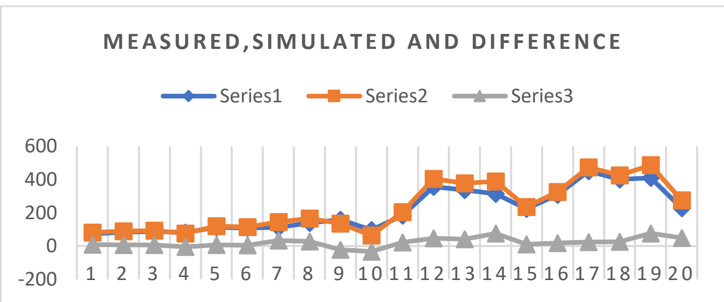

Figure 7: Data Validation Chart at 9:00 am (Source: Author, 2022)

Table 2: Measured luminance, simulated luminance, and variance at 4:00 pm

S/No.	Sensor Point	Measured (lux)	Simulated (lux)	Difference (lux)
1	G1	113.6	146.6	33
2	G2	204.83	248.7	43.87
3	G3	201.2	287.3	86.1
4	G4	225.5	276.5	51
5	G5	153.8	189.7	35.9
6	G6	245.5	297.7	52.2
7	G7	295.4	356.7	61.3
8	G8	337	367.4	30.4
9	G9	356	406.8	50.8
10	G10	182.6	265.7	83.1
11	G11	105	145.5	40.5
12	G12	145	193.4	48.4
13	G13	145	205.6	60.6
14	G14	115.6	157.3	41.7
15	G15	108.6	123.7	15.1
16	G16	125.6	147.8	22.2
17	G17	97.3	109.7	12.4
18	G18	105.4	127.4	22
19	G19	95.6	109.3	13.7
20	G20	105.6	133.6	28

Average measured illuminance = 173.2065
Average simulated illuminance = 214.8200

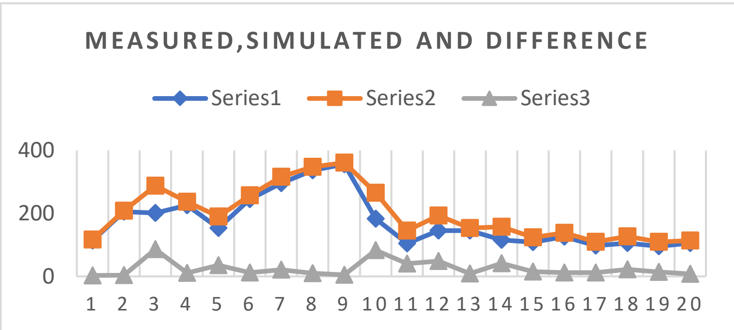

Figure 8: Data Validation Chart at 4:00 pm (Source: Author, 2022)

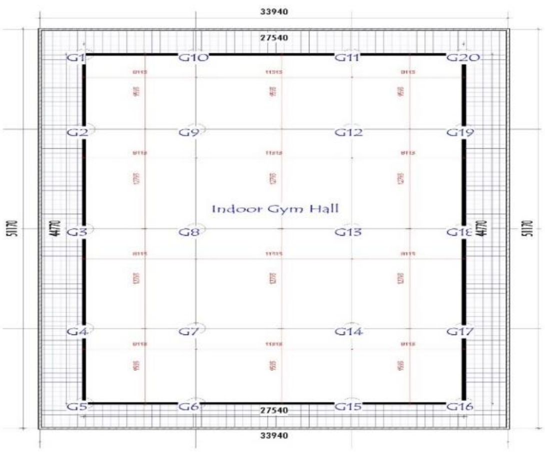

Figure 9: ABU Hall Grid Sensor Points for Data Collection (Source: Author, 2022)

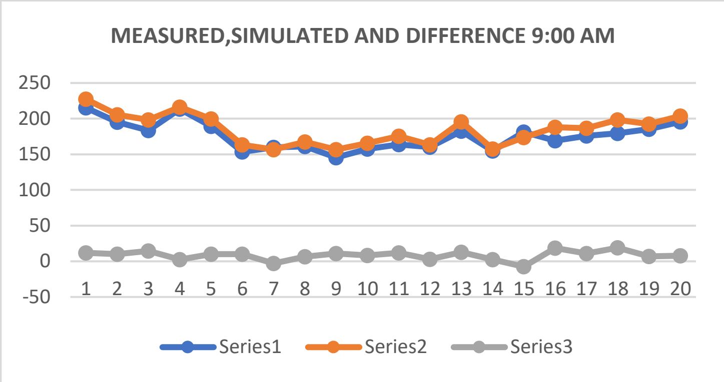

Figure 10: Validation Chart at 9:00 am, (Source: Author, 2022)

Table 4 shows the magnitude of the measured luminance at the 20 sensor points. The building parameters were utilized in developing a CBDM model that was analyzed to generate simulated luminance for every defined sensor point. The last column shows the difference between the measured and simulated luminance. The relationship between the values is graphically represented in the Figure 11.

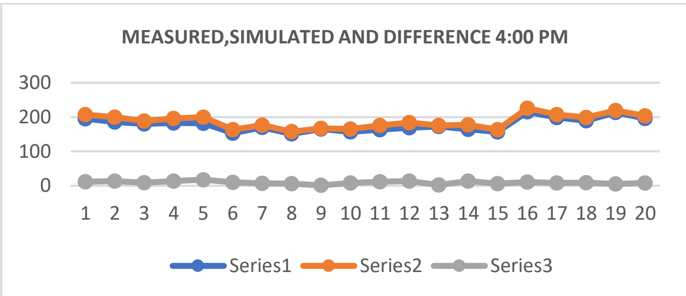

Figure 11: Data Validation Chart at 4:00 pm, (Source: Author, 2022)

Table 3: Measured luminance, simulated luminance, and variance at 9:00 am

S/No.	Sensor Point	Measured (lux)	Simulated (lux)	Difference (lux)
1	G1	215.2	227.3	12.1
2	G2	195.3	205.6	10.3
3	G3	183.7	198.4	14.7
4	G4	213.6	216.3	2.7
5	G5	189.4	199.7	10.3
6	G6	153.5	163.4	9.9
7	G7	159.7	156.7	-3
8	G8	160.9	167.4	6.5
9	G9	145.6	156.8	11.2
10	G10	157.3	165.7	8.4
11	G11	163.8	175.5	11.7
12	G12	160.4	163.4	3
13	G13	182.7	195.6	12.9
14	G14	154.9	157.3	2.4
15	G15	181.2	173.7	-7.5
16	G16	169.3	187.8	18.5
17	G17	175.8	186.7	10.9
18	G18	179.4	198.4	19
19	G19	185.5	192.3	6.8
20	G20	195.6	203.6	8

Average measured illuminance = 176.14
Average simulated illuminance = 184.58

Table 4: Measured luminance, simulated luminance, and variance at 4:00 pm

S/N	Sensor Point	Measured (lux)	Simulated (lux)	Difference (lux)
1	G1	195.2	207.3	12.1
2	G2	185.8	199.6	13.8
3	G3	179.7	188.4	8.7
4	G4	182.6	196.3	13.7
5	G5	181.8	199.7	17.9
6	G6	153.6	163.4	9.8
7	G7	169.7	176.7	7
8	G8	150.9	157.4	6.5
9	G9	165.6	166.8	1.2
10	G10	157.3	165.7	8.4
11	G11	163.8	175.5	11.7
12	G12	169.4	183.4	14
13	G13	172.7	175.6	2.9
14	G14	163.9	177.3	13.4
15	G15	157.2	163.7	6.5
16	G16	215.3	225.8	10.5
17	G17	198.8	206.7	7.9
18	G18	189.4	198.4	9
19	G19	213.5	219.3	5.8
20	G20	195.6	203.6	8

Average measured illuminance = 178.09

Average simulated illuminance = 187.53

4.1 Comparative Analysis of the findings from the Two Case Studies

Table 5 shows the assessment of daylight provision of the two case studies conducted with a checklist to investigate the levels at which the daylight design strategies were considered. The basis for the comparison of the two cases is that they are all purposely built as indoor sports halls and none is a converted structure, and was built with common construction materials available in the market and in a similar climate. Both cases utilized daylight during the daytime from windows, with exposure time from 9:00 am to 4:00 pm.

Figure 12 shows the differences in the measured illuminance of the two cases, and the differences in the variables studied, both utilize side lighting design strategies however, the concept of application differs. BUK utilizes direct side-lighting strategy while ABU utilizes in-direct-side lighting strategy, this accounts for the huge differences in the maximum and minimum illuminance of the two facilities.

Table 5: Comparison of the Two Case Studies Simulated and Measured Values

Illuminance	BUK	ABU	Difference Lux	Simulated Lux BUK	Simulated Lux ABU	Difference Lux
Min Lux 9:00 am	73	145.6	72.6	8.5	156.7	148.2
Max Lux 9:00 am	409.66	215.2	-194.46	486.3	227.3	-259
Min Lux 4:00 pm	95.6	150.9	55.3	116.6	157.4	40.8
Max Lux 4:00 pm	337	215.3	-121.7	360.8	225.8	-135

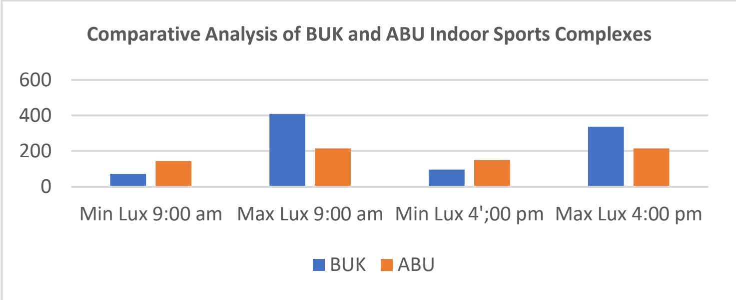

Figure 12: Comparison of Measured and Simulated Values (Source: Author, 2022)

4.2 Simulations of the Base Cases for Daylight Analysis

The base case for the analyses was modelled in DIALux-evo II for daylight simulation as shown in Figure 13, each of the base case involved in this research were modelled using the same floor area, window-floor ratio, same location, same orientation, same floor-to-ceiling height, same building material properties and finishes with same fenestration size and glazing material. For the purpose of this analysis three base cases were developed and utilized to test two daylighting design strategies:

1. Side-lighting (direct and in-direct)
2. Top-lighting

Figure 13 shows three base cases analyzed to optimally lit the indoor sports hall of size 20m x 20m, all the base cases were different in terms of positioning and daylight strategy. However, all other parameters of analysis were kept constant: global orientation, aperture size, glazing type and building materials properties. While Table 6 shows the daylight analysis parameters associated with the three base cases.

Table 6 also shows each base case with its defined light scene combination for analysis. The base cases were analyzed and the maximum and minimum daylight illuminance for optimal lighting of the indoor sports hall were determined. The experiment was iterated for quite a number of times until the optimum lighting requirement was reached based on Leadership in Energy and Environmental Design (LEED)'s lighting standards.

Plate 7 shows side-light aperture in place, size and properties of the aperture are displayed in the top most corners of the window. It shows side-lighting configuration based on the adopted parameters earlier defined.

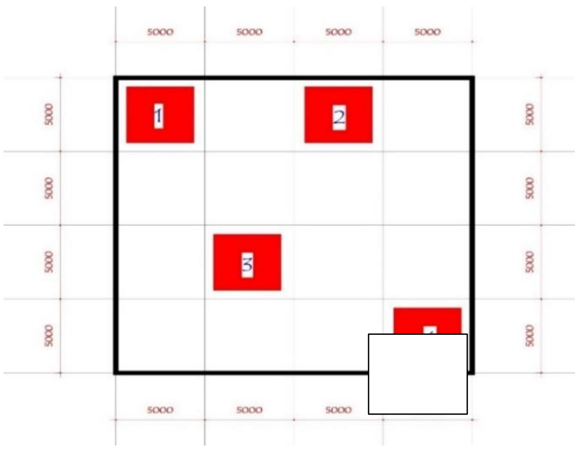

Figure 13: Base Cases for Analysis (Source: Author, 2022)

Table 6: Base Cases for Analysis (Day light combinations)

Base Cases	Sidelight	Top-Light	Light Scheme Combination
1	Side light on two external walls	60% of the roof area	side-light and top-light
2	Side light on one external wall	60% of the roof area	side-light and top-light
3	No defined side light	60% of the roof area	Only top-light

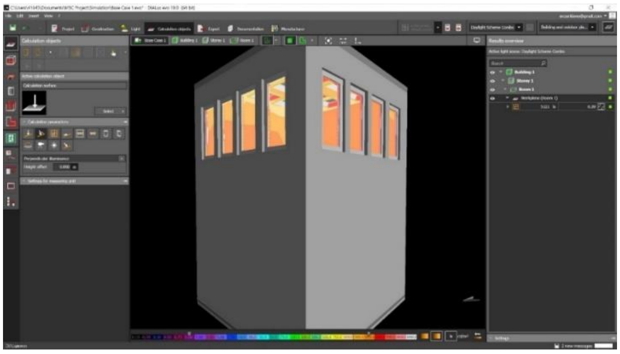

Plate 7: Side Light Combo (Source: Author, 2022)

The experiment was slated for a combination of lighting schemes for all the base cases to determine the feasibility of achieving optimum daylight in the indoor sports hall, a light scheme combo of side-light and top-light was developed and analyzed. Plate 8 shows the configuration of the defined daylighting schemes for the analysis. All the base cases were experimented based on the lighting strategy defined for its combination.

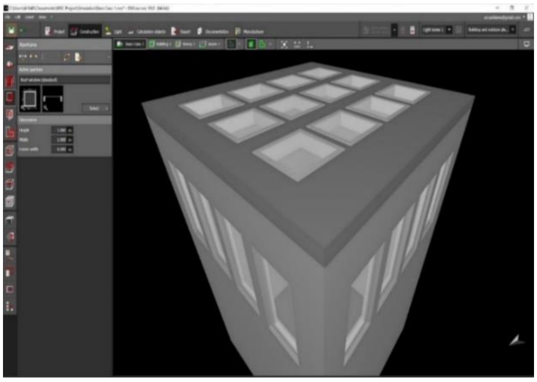

Plate 8: Daylight Scheme Combined (Source: Author, 2022)

4.3 Base Case 1

This case was based on side-light on two external walls and top-light, illuminance recorded ranged between 1575 lux and 5212 lux, Plate 9 shows the recorded illuminance for the light scheme Base Case 1. Figure 15 shows the summary of daylight analysis for the base case 1, the result shows that an illuminance of over 500 lux was recorded for all the 64 sensor points, with a daylight factor (D) 8.12%, a perpendicular illuminance (E) of 5121 lux and uniformity index (g) of 0.29.

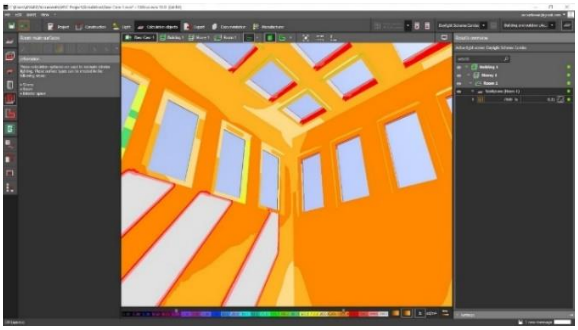

Plate 9: Base Case 1 Pseudo Color Chart (Source: Author, 2022)

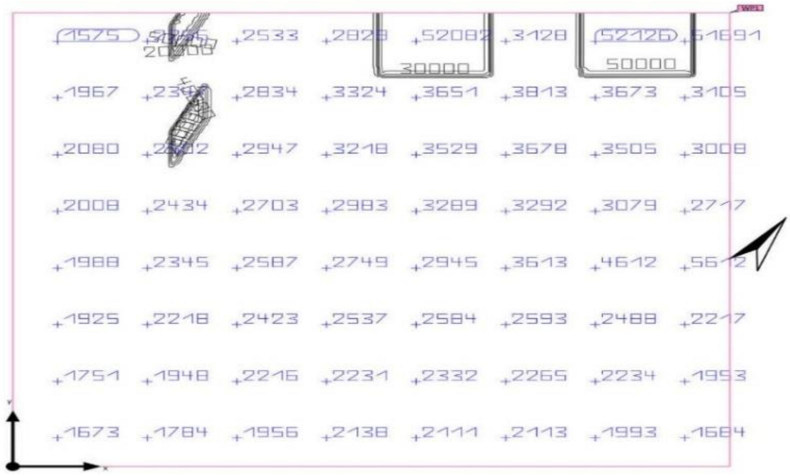

Figure 14: Recorded Illuminance Base Case 1 (Source: Author, 2022)

Results

	Symbol	Calculated	Target	Check	Index
Daylight	D	8.121 %	-	-	DF1
Workplane	$\bar{E}_{perpendicular}$	5121 lx	≥ 500 lx	✓	WP1
	g_1	0.29	-	-	WP1
Consumption values	Consumption	0 kWh/a	max. 50 kWh/a	✓	
Room	Lighting power density	0.00 W/m²	-	-	
		0.00 W/m²/100 lx	-	-	

Figure 15: Summary Results for Base Case 1 (Source: Author, 2022)

4.4 Base Case 2

Side-light on one external wall and top-light, illuminance recorded ranged between 1427 lux and 5191 lux, Plate 10 shows the recorded illuminance for the light scheme combination of Base Case 2.

4.5 Results for Base Case 2

Figure 17 shows the summary of daylight analysis for base case 2, the result shows that an illuminance of over 500 lux was recorded for all the 64 sensor points with a daylight factor (D) 6.931%, a perpendicular illuminance (E) of 4551 lux and uniformity index (g) of 0.31.

4.6 Base Case 3

No side-light on external walls and only top-light, illuminance recorded ranged between 1439 lux and 5197 lux. Plate 11 shows the recorded illuminance for light scheme combination of Base Case 3.

Figure 19 shows the summary of daylight analysis for base case 3, the result shows that an illuminance of over 500 lux was recorded for all the 64 sensor points with a daylight factor (D) 5.718%, a perpendicular illuminance (E) of 4481 lux and uniformity index (g) of 0.31.

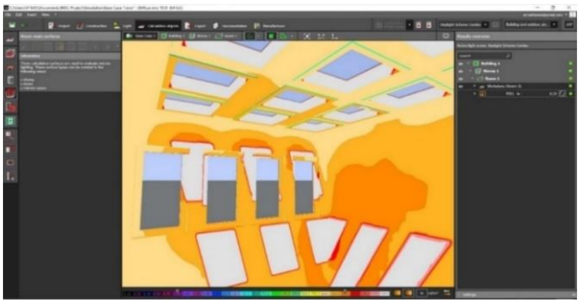

Plate 10: Base Case 2 Pseudo Color Chart (Source: Author, 2022)

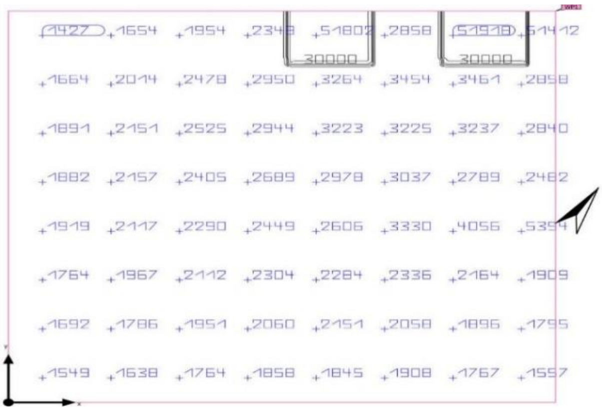

Figure 16: Recorded Illuminance Base Case 2 (Source: Author, 2022)

Results

	Symbol	Calculated	Target	Check	Index
Daylight	D	6.931 %	-	-	DF1
Workplane	$\bar{E}_{perpendicular}$	4551 lx	≥ 500 lx	✓	WP1
	g_1	0.31	-	-	WP1
Consumption values	Consumption	0 kWh/a	max. 50 kWh/a	✓	
Room	Lighting power density	0.00 W/m²	-	-	
		0.00 W/m²/100 lx	-	-	

Figure 17: Simulation Summary for Base Case 2 (Source: Author, 2022)

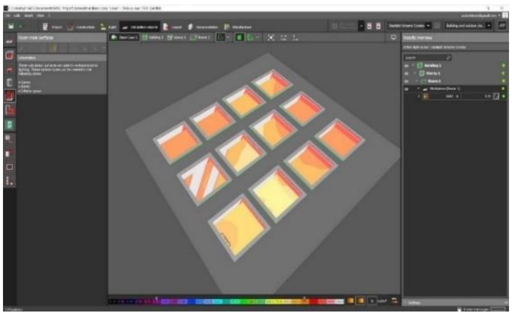

Plate 11: Base Case 3 Pseudo Color Chart (Source: Author, 2022)

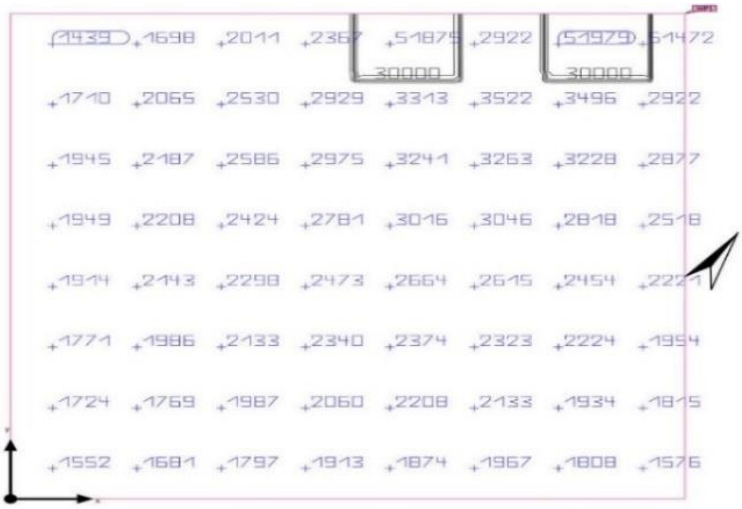

Figure 18: Recorded Illuminance Base Case 3 (Source: Author, 2022)

Results

	Symbol	Calculated	Target	Check	Index
Daylight	D	5.718 %	-	-	DF1
Workplane	$\bar{E}_{perpendicular}$	4481 lx	≥ 500 lx	✓	WP1
	g_1	0.31	-	-	WP1
Consumption values	Consumption	0 kWh/a	max. 50 kWh/a	✓	
Room	Lighting power density	0.00 W/m²	-	-	
		0.00 W/m²/100 lx	-	-	

Figure 19: Results for Base Case 3 (Source: Author, 2022)

5. CONCLUSION

A critical analysis of the results of the simulation experiments carried out on the base cases revealed that side light alone does not provide sufficient lighting and also results in over illumination of the immediate areas around the opening and under illumination of areas further away from them. Top light, on the other hand, provides adequate lighting in the exact positions of the skylight, therefore does not cater for all the visual task areas. A combination of the two strategies (side light and top light), does provide the required illumination and also aid in achieving uniform distribution of light which results in optimum daylighting of indoor halls. Table 7 shows the summary of the results from the daylight analysis of the three base cases. The results show the daylight distribution across all the base cases, thus, showing the effectiveness of the light scheme combinations. The analysis also shows the lapses of the application if only one of the daylight strategies is used, therefore, optimum lighting is achieved with combination of two strategies.

The chart in Figure 20 shows the close relationship between the recorded values of maximum illuminance (E_{max}), minimum illuminance (E_{min}) and perpendicular illuminance (E) of all the base cases.

Table 7: Maximum, Minimum and Perpendicular Illuminance

S/No.	**Base Case**	**E_{max}**	**E_{min}**	**Perpendicular Illuminance (E)**
1	Base Case 1	5212	1575	5121
2	Base Case 2	5191	1427	4551
3	Base Case 3	5197	1439	4481

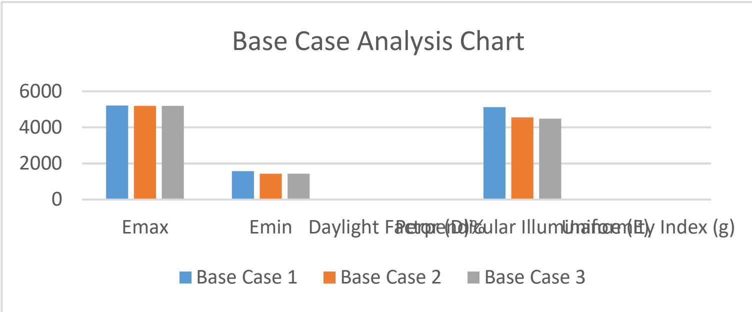

Figure 20: Comparison E_{min} and E_{max} of Base Cases (Source: Author, 2022)

6. RECOMMENDATIONS

The research has succeeded in providing parameters and design strategies to optimally light indoor sports halls considering heat gain from fenestration and direct and indirect glare. The analysis shows the lapses of the application if only one of the daylight strategies is used (that is either using side light or top light only) therefore, optimum lighting is achieved with combination of the two strategies; side and top lighting schemes. It also reinforces the use of two technologies: adaptive shading and the selective reflector light shelf. The emergence of such technologies is crucial to the continuous development of high-performance buildings facades. The adaptive overhang can increase indirect daylight illumination intensity while maintaining shaded window areas. Furthermore, the selective reflector light shelf increased daylight performance while limiting the energy for cooling the indoor environment significantly.

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