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Research Article

The Effect of Atrium Roof Forms on the Day Light Performance of Atrium and Adjoining Spaces: An Analytical Study

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ABSTRACT

Daylight is a key component of a sustainable environmental approach to the building design. An atrium is a major source which allows the maximum daylight to come inside the deep plan building which reduces the demand of artificial light hence leads to an energy efficient building design. However, direct sunlight is problematic because of a source of glare which increases the thermal heat gain inside the building. The key atrium components are the roof fenestration system, the geometry of the atrium well, the reflectance of the well's surfaces and the daylight levels achieved in spaces adjacent to the well. This paper describes the various atrium roof forms and its performance by simulating different types of atrium roof 3D model. Day lighting analysis was done using Climate Studio tool with Rhinoceros 3D 7.0. Built on Energy Plus and a novel RADIANCE-based path tracing technology.

Keywords: Daylight, Atrium roof design, Building orientation, Software simulation, Average lux, Special daylight autonomy, Annual sunlight exposure

INTRODUCTION

The building sector is responsible for the biggest single contributor to world energy consumption. As per IEA, the operations of buildings account for 30% of global final energy consumption. The buildings and its construction sector accounted for 36% of final energy use.

Building Sector in India has doubled its floor space between 2001 to 2005 and expected to add 35 billion square meters of new buildings by 2050. Currently, buildings account for 35% of total energy consumption and growing at 8% annually. As per a report of the Royal Institution of Chartered Surveyors (RICS), 4127 million square meter of real estate space (which includes residential, retail, offices, hotels, health care and education sectors) is expected to be built between 2012 and 2020 which is on an average construction of 460 million square meter of real estate space per year. [1]

Rapid urbanization bodes well for the sector. The number of Indians living in urban areas is expected to reach 525 million by 2025 which expected to add 35 billion square meters of new buildings by 2050. In India Buildings sector (residential and commercial) constitutes 33% of total electricity consumption. If current scenario continues, buildings will demand 55% of total electricity generated by 2047. Commercial buildings consume about 9% of total electricity consumption. Commercial buildings include offices, hospitals, hotels, retail outlets, educational buildings, government offices, etc. The total built-up area of commercial buildings is expected to touch 1.9 billion m2 by 2030. The rate of growth in commercial buildings sector is amongst the highest [2].

Energy efficiency in buildings is becoming very important aspects so; building designers are playing a vital role to achieve more and more energy efficient design. There has been also eagerness to find a design more effective to cut down the energy demand. For buildings in general and commercial buildings using artificial lighting is considered a key problem that can lead to excessive energy uses as it affects cooling and heating load requirements of the building [8]. Many building designers attempt the possibilities by incorporating courtyard and atrium in the building to enhance the daylight performance, consequently minimizing the artificial lighting load and hence reduce the electrical energy demand in the building. Globally, out of the total energy consumption in building sector building lighting share 19 % approximately electric energy consumption [9].

A major component of the environment and sustainable solutions to the energy performance of a building is the replacing or supplementing artificial lighting use by daylight. For daylight design the key atrium components are the roof fenestration system, the geometry of atrium well, the reflectance of well surfaces and the daylight levels achieved in space adjacent to the space [10].

The components of a daylighting system are designed to bring natural light into a building in such a way that electric lights can be dimmed or turned off for a portion of the day, while preventing occupant discomfort or other building loads from increasing. For example, direct sun in the eye of a building occupant can cause disability glare, which interferes with the occupant's ability to see and perform work and should be avoided [11].

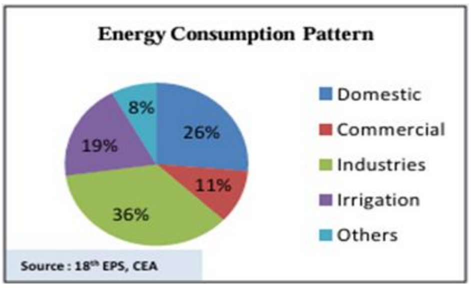


Figure 1: Energy consumption Pattern globally

Glare. The aim of an efficient daylighting design is not only to provide illuminance levels that are sufficient for good performance, but also to maintain a comfortable and pleasing atmosphere. Glare, or excessive brightness contrast within the field of view, is an aspect of lighting that can cause discomfort to occupants. The human eye can function quite well if extreme levels of brightness are present in the same field of view [11].

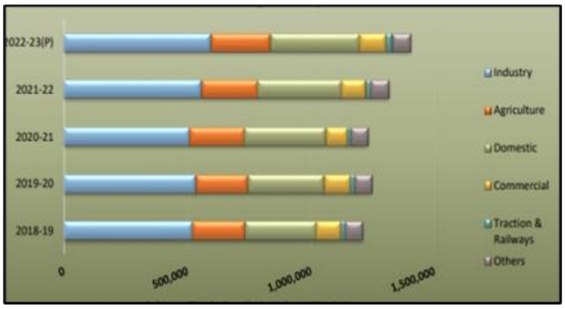


Figure 2: Sector wise consumption of electricity during last 5 years in India

Effect of daylight on the occupants

Adequate daylight causes many benefits to the building occupants. It imparts not only visual comfort to the occupants but also have lots of health benefits. Many researches showed that daylighting can reduce the mental and physical strain of patients, doctors and other medical staff. Improving the mental well-being of patients improves their recovery rate.

"Daylighting offers a sense of spirituality, openness and freedom from the prison – like confinements and intensity that characterize windowless space" (Verdure 1983).

Adequate light received during the natural day period synchronises the internal biological clock, stimulates circulation, increases the production of vitamin D, regulates protein metabolism, and controls the levels of a number of hormones such as cortisol (the 'stress hormone') and melatonin (the 'sleep hormone') [12].

Other than providing potential energy savings, daylight can foster significant advantages to the quality of architectural spaces, bringing benefits to the health of people that live in buildings, and to the finances of the organisations commissioning them.

However, daylight is endowed with unique features which are conducive to human health, as it is generally delivered in large quantities and ensures a continuous variation in spectral content, thus presenting an effective stimulation for the human circadian system. Daylight should be valued as a necessity that drives and directs the design from its early stages, ultimately leading to better architecture which is cheaper to run, less harmful for the environment, and healthy and stimulating for its users [12].

Atrium roof design

There has been a general approach to find the effective and efficient design strategies to cut down to the energy demand of building by achieving energy efficient design. In general, the use of artificial lighting is the main problem that leads to excessing energy use as it affects the cooling and heating requirement of the building. Incorporating courtyard or atrium in to a building may increase the daylight inside the building and thus this can lead to the more energy efficient building design.

An atrium is a major source of daylight for deep plan buildings and also results in other environmental benefits in terms of solar gain, reduced energy losses and natural ventilation. For daylight design, the key atrium components are the roof fenestration system, the geometry of the atrium well, the reflectance of the well's surfaces and the daylight levels achieved in spaces adjacent to the well.

The geometry of atrium plays very important role in energy efficiency and in daylight perspective. In all climatic regions, the effect of the atrium geometry has been found to be more evident in the elongated atrium shapes and this is due to the size of the skylight exposed to environmental conditions [5].

All aspects of the atrium in buildings such as atrium proportion, orientation, shape and size, height, shading control of the atrium, atrium’s glazing type and ratio, and the thermal mass of the atrium’s walls, need careful design consideration.

Analysis of different types of atrium roof were done by Navvab and Selkowirz (1984), it was found that Sawtooth and monitor configuration have the maximum day light in comparison to pyramid, vaults and A frames. As per Boubekri (1995) the flat roof can cater more daylight while sawtooth roof having the strongest directional properties which receives most light on the walls that faces the opening of the roof. And hence the roof structure design has the greatest effect on daylight intensity. Sawtooth roofs admitted half of the diffuse skylight of the baffle roof under overcast condition. It blocking out the summer sun and allowing low altitude sun thus increase the heat gain in winter. [10]

RESEARCH AND METHODOLOGY

The most important interior elements which have effect on the amount of daylight in the adjacent spaces of atria are: (1) atrium roof system and its fenestrations, (2) type, shape, orientation and geometry of atrium well, (3) atrium's enclosing surfaces includes atrium facade design walls and floor reflectance and (4) characteristics of adjoining spaces consist of size, surfaces reflectance and so on [13].

This study is focused on the effect and analysis of different types of atrium roof truss on daylight and glair in atrium and adjacent space. Purpose of this study is to find out how the atrium roof structure in a variety of shape and size affect the daylighting environment in the adjoining space of atrium. The daylight simulation results and other simulation results will be discussed in this paper.

The Daylight Factor (DF) is one of the important parameters to check the atrium performance at different variable conditions.

Daylight factor (DF) = (Indoor illuminance at a fixed point/Outdoor illuminance under an overcast or uniform sky) x 100

According to the standard of Illuminating Engineering Society (IESNA), an average daylight factor of less than 2% means that the room is poorly lit and artificial lighting is necessary. In contrast, an average daylight factor of more than 5% means that the room is well lit. According to the British standard of lighting for building (BS 8206 part 2), the minimum acceptable daylight factor is 2%.

According to the guidelines of Chartered Institution of Building Service Engineers (CIBSE), if the average daylight factor is more than 5% or more the room receives more than sufficient light during the day except around early morning or late afternoon, but if daylight factor is 2% or less, the room must be categorized as poorly lit and be given proper artificial lighting.

The daylight factor also called as the natural light condition of a space. The daylight factor can be divided into three components: the sky component (SC), that which comes directly from the sky, the externally reflected component

(ERC), that which has been reflected by external obstructions (e.g. buildings, trees, the ground) and the internally reflected component (IRC), that which has been reflected off internal room surfaces. DF = SC + ERC + IRC. [14]

Software Description

The day lighting analysis is being done using Climate Studio tool with Rhinoceros 3D 7.0. It's simulation workflows helps designers and consultants optimize buildings for energy efficiency, daylight access, electric lighting performance, visual and thermal comfort, and other measures of occupant health. Built on Energy Plus and a novel RADIANCE-based path tracing technology. The workflow followed was Daylight Simulation:

Spatial Daylight Autonomy and Annual Sunlight Exposure, this workflow supports the calculation of spatial daylight autonomy 300/50% (sDA300/50%), and annual sunlight exposure1000,250 (ASE1000,250) as defined in IES LM-83-12 for regularly occupied space. Additionally, it also calculates the average sDA 300/50% value for the total regularly occupied floor area.

Model Description

A detailed 3-D model having size 20 mt. x 16 mt. with height 6 mt. and atrium size of 6 mt., x 10 mt. of virtual project is being created in Rhinoceros 3D 7.0. The daylight performance will be simulated using Climate Studio. The virtual location of the site is at Patna, Bihar, India. Hence EPW File of Patna, Bihar, India's is being used in this model. The external shading devices will be kept opaque as day lighting results will be analysed only through the atrium and the internal walls all around along the atrium is kept transparent to examine the simulation results in of atrium adjoining areas. Each atrium is of rectangular in size and total four numbers of atrium roof model, each model total three simulation results will be discussed in three orientations that is north –south orientation, east – west orientation and 45 degrees to east to north orientation.

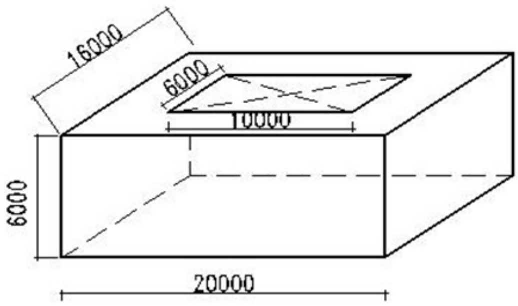


Figure 3: 3-D software model with dimensions, the virtual location of the site is at Patna, Bihar, India

Software Simulation

IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) is define a consistent methodology that would allow for daylight design comparisons to be evaluated in a common language by building codes or design guidelines. Fundamental daylight metrics were lacking in the industry that could be used to assess the entire daylight area for an entire year, considering climatic variables. The two metrics described in IES LM-83-12 allow for the calculation of adequate daylight illuminance and the potential risk of excessive sunlight entering the regularly occupied floor area. (IES, 2012).

The first metric is Spatial Daylight Autonomy (sDA), a measure of daylight illuminance sufficiency for a given area, reporting a percentage of floor area that exceeds a specified illuminance level for a specified number of annual hours.

The second metric is Annual Sunlight Exposure (ASE), which provides a second dimension of daylight analysis, looking at one potential source of visual discomfort: direct sunlight (IES, 2012).

The sDA metric measures an illuminance threshold on horizontal surfaces to first assess the number of hours per year that each analysis point within a given analysis area meets or exceed this value from daylight along. The Daylight conditions are based on typical meteorological year (TMY) data with an analysis time period extending from 8AM to 6PM local time. sDA 300/50% sets the illuminance threshold at 300 lux which must occur for 50% or more occupied hours of the year.

The Annual Sunlight Exposure has less than 250 hours per year with an illuminance measured of 1,000 lux (ASE1000,250h) of direct sunlight.

Climate studio daylight simulation plugin/software programs were chosen to evaluate the sDA300/50% results. Climate studio tool uses the Radiance engine for the annual climate-based simulations. Climate Studio simulates the behaviour of light using Radiance, an industry-standard, physically-based engine developed and maintained by Lawrence Berkeley National Laboratory. But unlike its predecessors, Climate Studio Implements Radiance in a *progressive path tracing* mode. That is, rather than tracing all possible light paths before computing a result, Climate Studio traces a few paths at a time, updating the result as it goes. By combining progressive path tracing with hardware acceleration.

Climate based daylight modelling (CBDM)

CBDM is the dynamic analysis (over time) of daylight levels using a combination of sky types which are then modified by cloud cover or solar data from a selected simulation weather file. Climate based daylight modelling delivers predictions of illuminance or daylight factor over time which are dependent on the site location, building orientation, glazing and configuration.

CBDM is used for assessments for many voluntary rating systems. For all the assessments, the calculation uses a grid to represent the working plane, which is then used to determine the daylight performance of the space.

Three types of CBDM can be undertaken using Radiance IES:

1. Annual Sunlight Exposure (ASE)
2. Spatial Daylight Autonomy (sDA)
3. Useful Daylight illuminance (UDI) [17]

Table 1: 3-D software model in climate studio with four types of sky light roof.

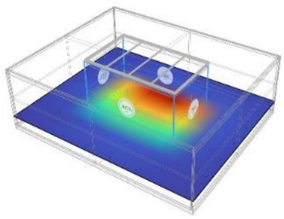
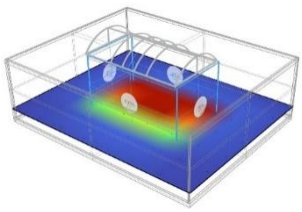
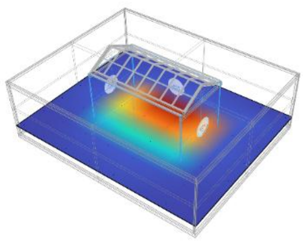
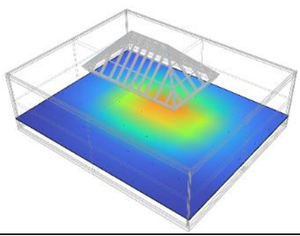
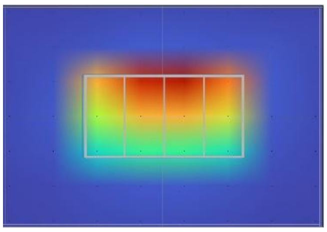
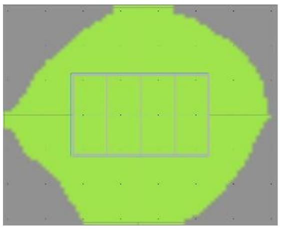
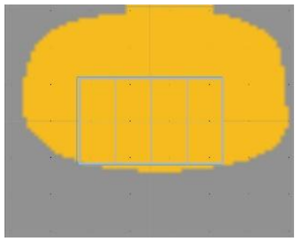
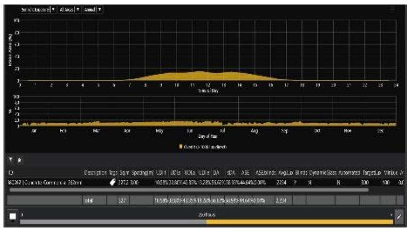
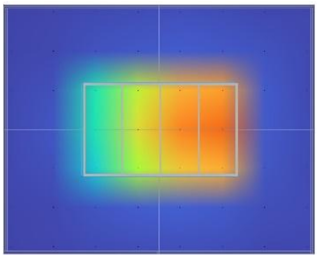
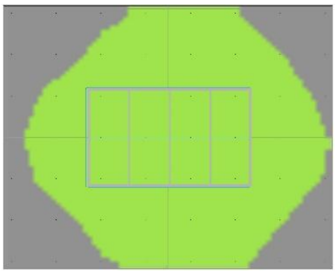
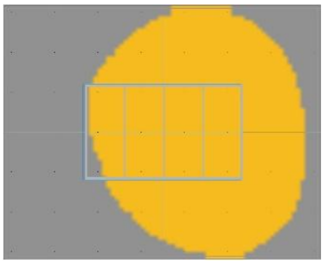
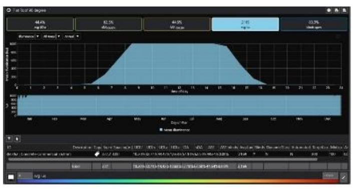
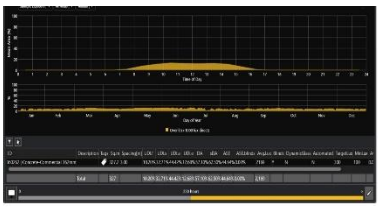
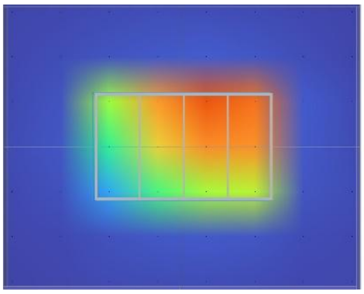
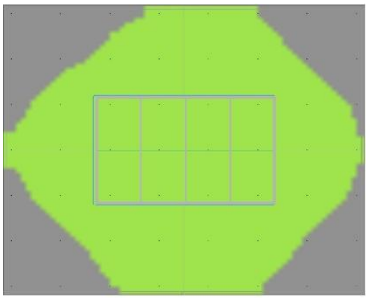
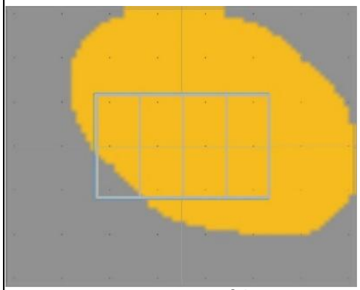
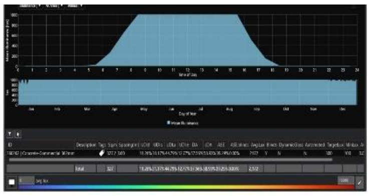
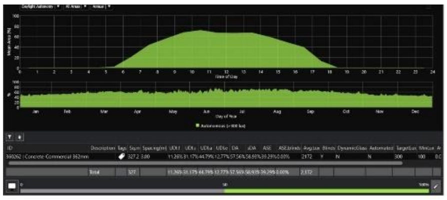
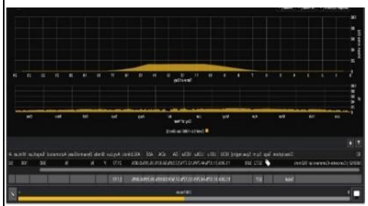
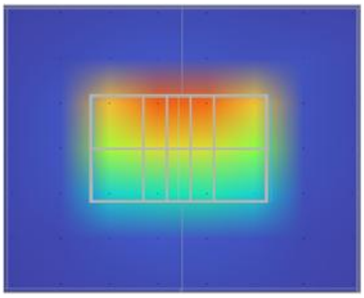
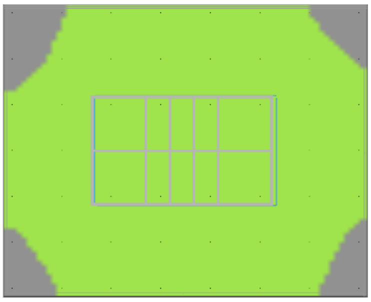
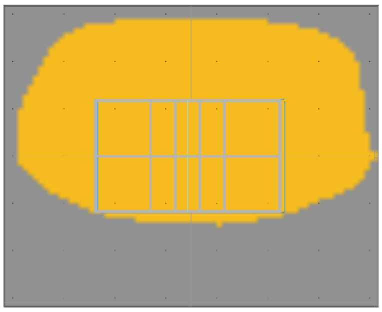
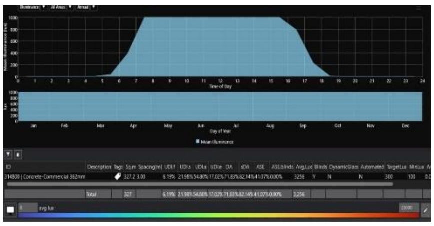
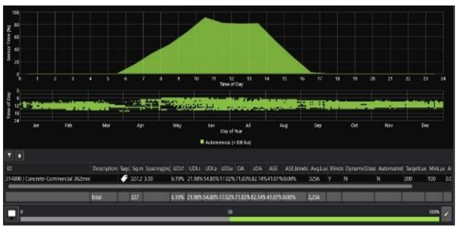
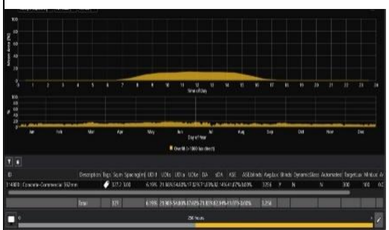
Options	Roof Type	3D Model
1.	**Flat skylight Roof**	
2.	**Continuous Barrel Skylight Roof**	
3.	**Gable End Skylight Roof**	
4.	**Hip End Skylight Roof**	

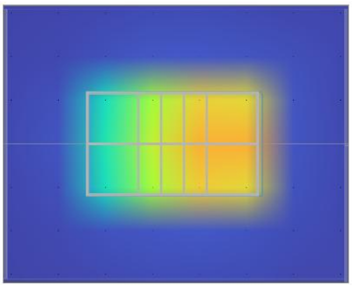
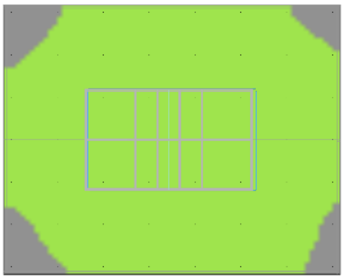
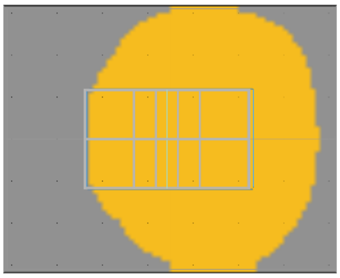
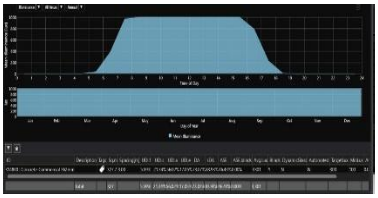
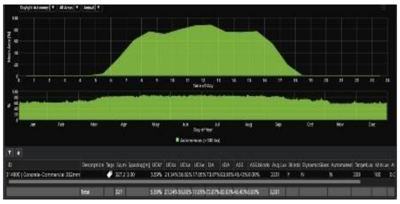
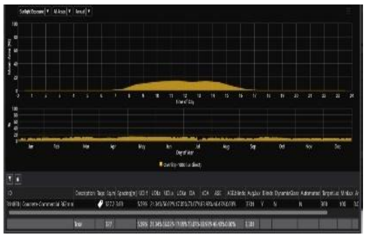
Table 2: 3-D software simulation results of four types of sky light roof

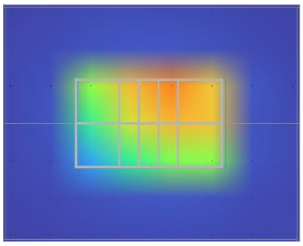
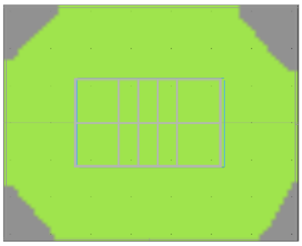
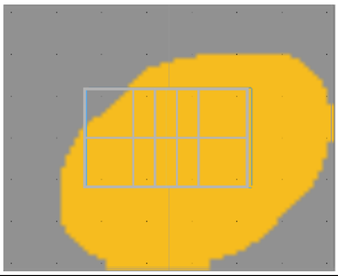
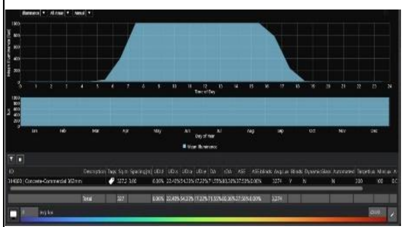
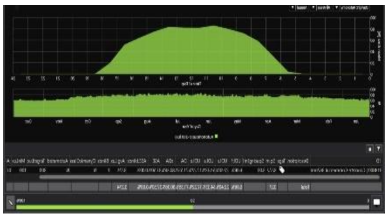
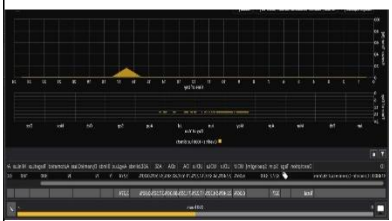
Models in climate studio showing average lux, Spatial Daylight Autonomy and Annual Sunlight Exposure

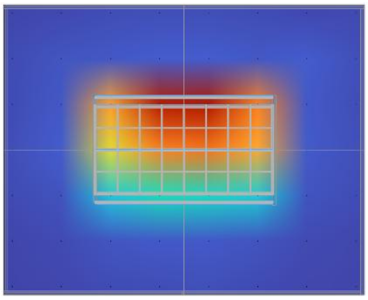
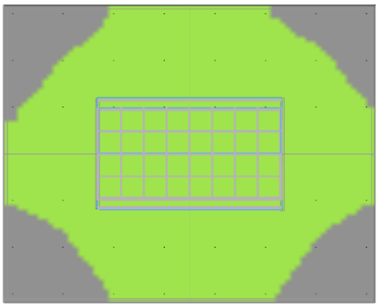
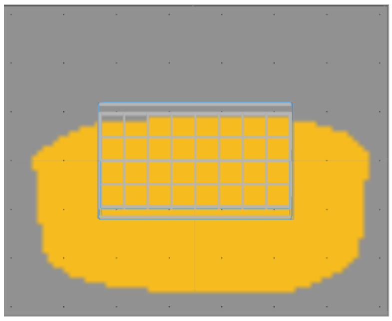
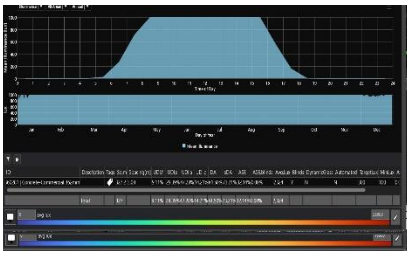
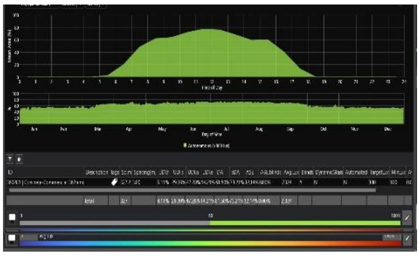
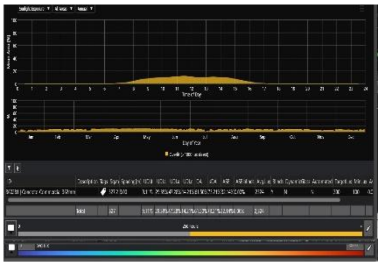
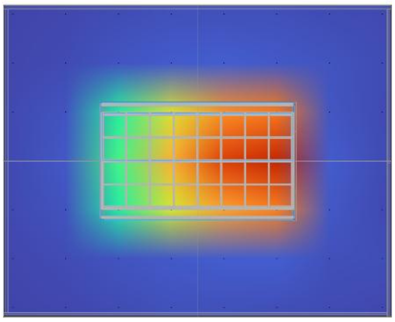
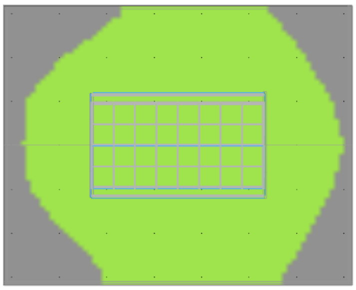
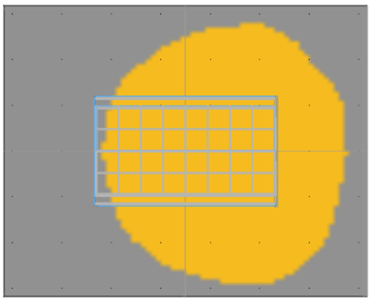
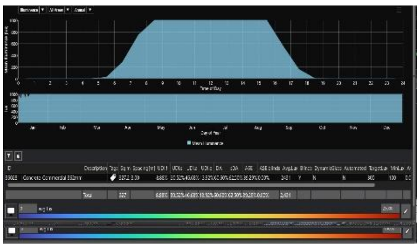
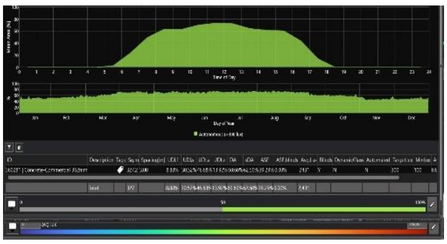
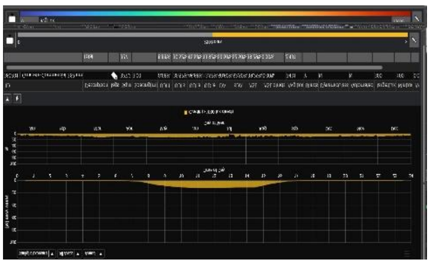
Results: Option – 1 A - Flat Roof skylight, NORTH-SOUTH Orientation		**N**
Average Lux	**Spatial Daylight Autonomy (sDA)** (>300 lux, 50% occupied hrs)	**Annual Sunlight Exposure (ASE)** (>1000 lux direct, 250 hrs)
 2234 Lux	 58.9%	 44.6%
		
Results: Option – 1 B - Flat Roof skylight, EAST-WEST Orientation		**N**
 2169 Lux	 62.5%	 44.6%
		

Results: Option – 1 C - Flat Roof skylight, EAST-NORTH Orientation	**N**

Average Lux	**Spatial Daylight Autonomy (sDA)** (>300 lux, 50% occupied hrs)	**Annual Sunlight Exposure (ASE)** (>1000 lux direct, 250 hrs)
 2172 Lux	 58.9 %	 39.3 %
		
Results: Option – 2 A - Continuous Barrel roof skylight, NORTH-SOUTH Orientation		**N**
 3256 Lux	 82.1 %	 41.1 %
		

Results: Option – 2 B - Continuous Barrel roof skylight, EAST-WEST Orientation		**N**
Average Lux	**Spatial Daylight Autonomy (sDA)** (>300 lux, 50% occupied hrs)	**Annual Sunlight Exposure (ASE)** (>1000 lux direct, 250 hrs)
 3301 Lux	 83.9 %	 46.4 %
		

Results: Option – 2 C - Continuous Barrel roof skylight, EAST- NORTH Orientation		**N**
 3274 Lux	 80.4 %	 37.5 %
		

<table>
<tr><td colspan="2">Results: Option – 3A - Gable End Skylight Roof,
NORTH-SOUTH Orientation</td><td>N</td></tr>
<tr><td>Average Lux</td><td>Spatial Daylight Autonomy (sDA)
(>300 lux, 50% occupied hrs)</td><td>Annual Sunlight Exposure (ASE)
(>1000 lux direct, 250 hrs)</td></tr>
<tr><td>
2324 Lux</td><td>
73.2 %</td><td>
32.1 %</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td colspan="2">Results: Option – 3 B - Gable End Skylight Roof,
EAST-WEST Orientation</td><td>N</td></tr>
<tr><td>
2431 Lux</td><td>
62.5 %</td><td>
39.3 %</td></tr>
<tr><td></td><td></td><td></td></tr>
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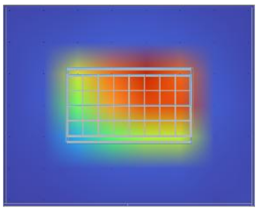
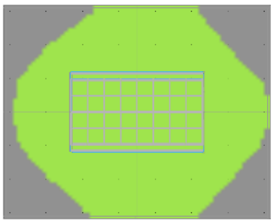
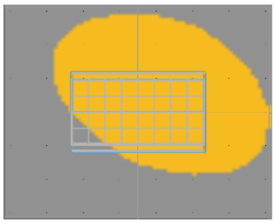
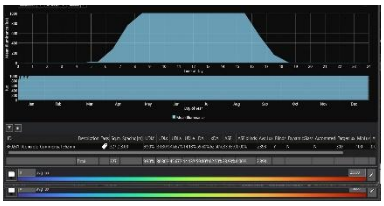
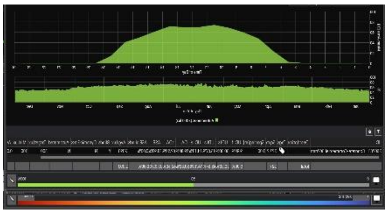
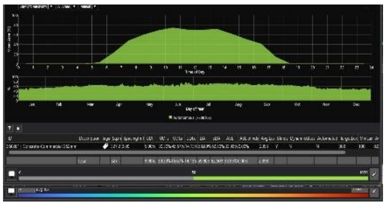
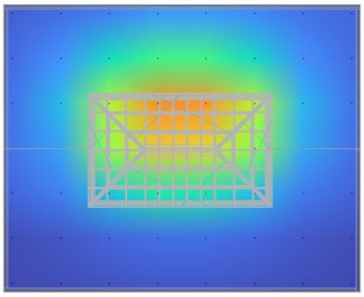
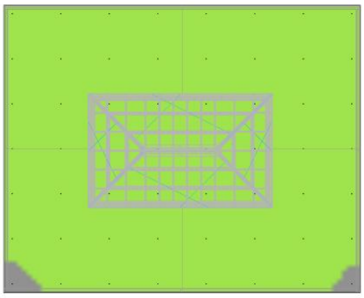
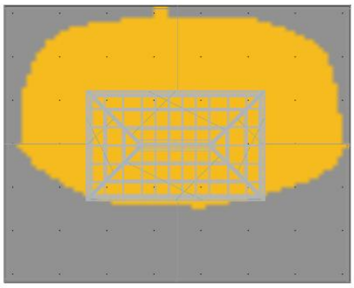
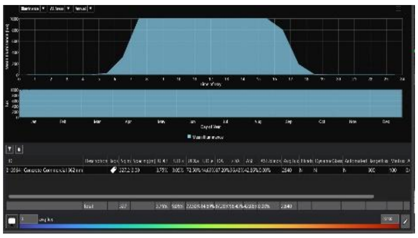
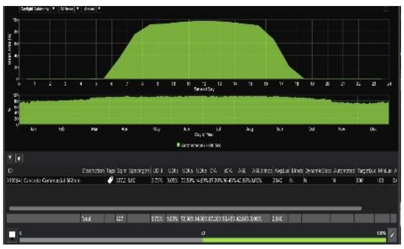
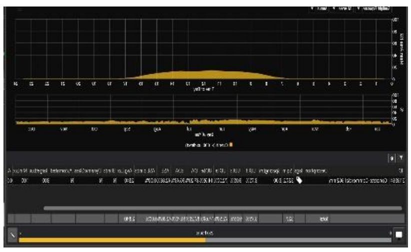
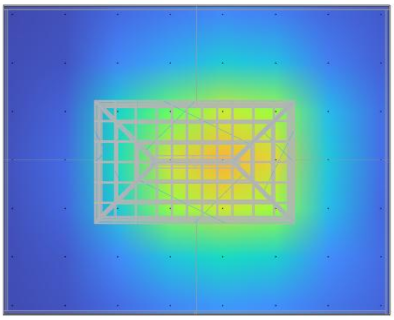
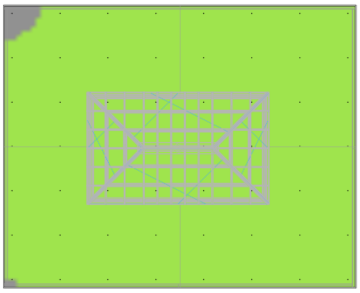
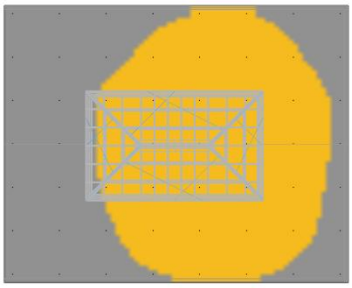
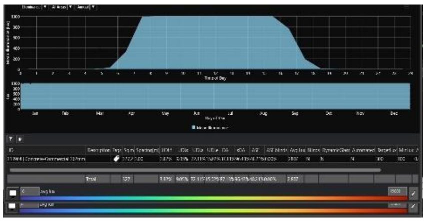
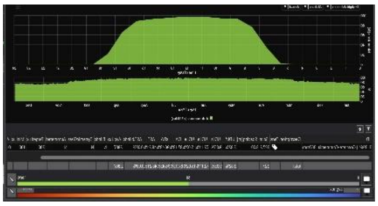
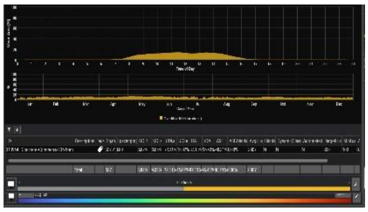
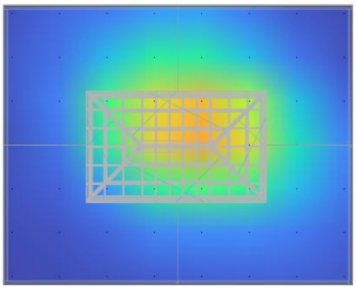
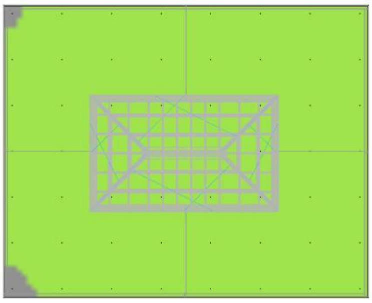
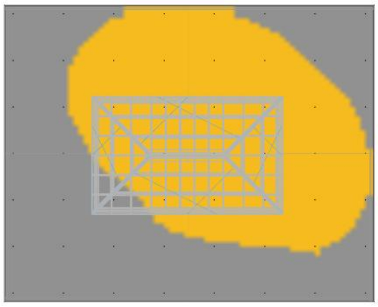
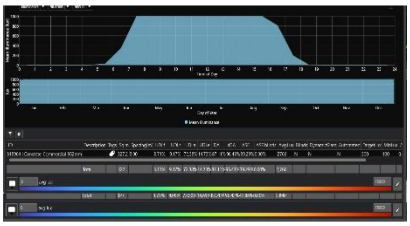
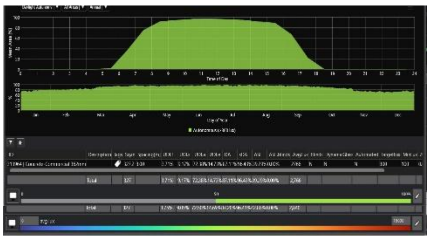
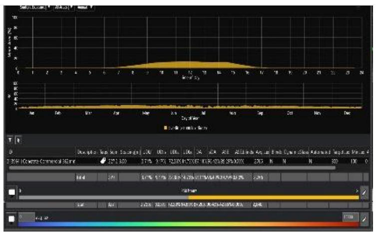
Results: Option – 3 C - Gable End Skylight Roof, EAST-NORTH Orientation		**N**
Average Lux	**Spatial Daylight Autonomy (sDA)** (>300 lux, 50% occupied hrs)	**Annual Sunlight Exposure (ASE)** (>1000 lux direct, 250 hrs)
 **2393 Lux**	 **62.5 %**	 **33.9 %**
		
Results: Option – 4A - Hip End Skylight Roof, NORTH - SOUTH Orientation		**N**
2840 Lux 	 96.4	42.9 % 
		

Results: Option – 4B - Hip End Skylight Roof, EAST - WEST Orientation		**N**
Average Lux	**Spatial Daylight Autonomy (sDA)** (>300 lux, 50% occupied hrs)	**Annual Sunlight Exposure (ASE)** (>1000 lux direct, 250 hrs)
 2807 Lux	 96.4 %	 48.2 %
		
Results: Option – 4C - Hip End Skylight Roof, EAST - NORTH Orientation		**N**
 2766 Lux	 96.4 %	 39.3 %
		

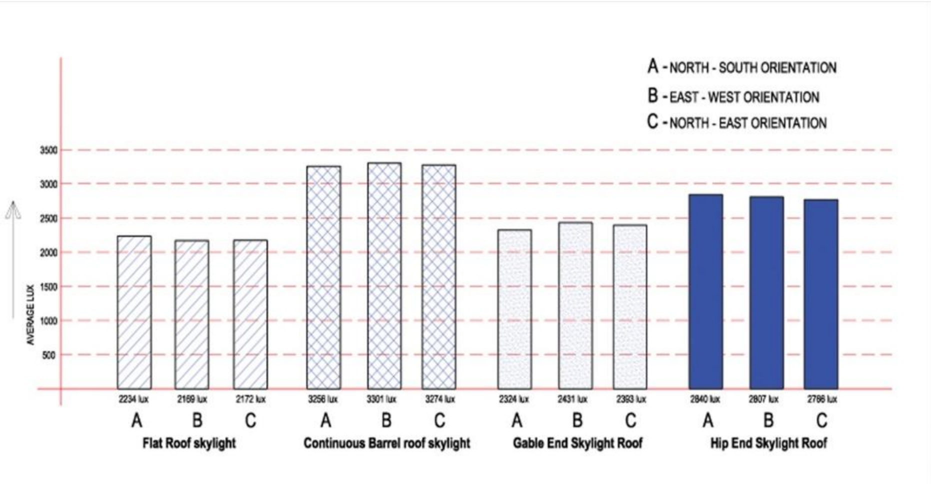


Figure 4: The average daylight level of different roof with orientation are shown in the above table

CONCLUSION

The daylight analysis of the building models using various skylight options revealed the following key results:

Option 2 (Continuous Barrel Skylight) and Option 4 (Hip End Skylight) demonstrated high levels of average lux 3301 and 2840 Lux, respectively (in north south orientation) and spatial daylight autonomy 82.1% & 96.4% respectively (in north south orientation), indicating effective daylight penetration.

Option 3 (Gable End Skylight) showed a balanced performance with moderate average lux (2324 Lux) and a lower ASE (32.1%), reducing the risk of discomfort due to excessive sunlight exposure, while still achieving 73.2% daylight autonomy.

Option 1 (Flat Roof Skylight) performed a lower average lux 2234 lux (in East – North orientation), which might result in reduced daylight levels compared to other options.

Observation

The analysis highlights a trade-off between maximizing daylight and controlling excessive sunlight exposure. Skylight designs such as the Gable End Skylight in North – South & North – East orientation and Continuous Barrel Roof in East – North orientation is more effective in mitigating the risks of glare and overheating while still providing adequate daylight. Therefore, the choice of skylight design must balance daylight autonomy with occupant comfort, considering the building's functional requirements and location.

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