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Effect of Daylighting Design on Sunlight Accessibility and Visual Comfort in Top-Lit Atriums for Business Building Structures

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ABSTRACT

The need for energy efficiency has grown significantly in recent years, along with environmental concerns. As a result, building designers are now more attentive to natural ventilation in the summer, employing daylight as a source of energy for buildings, and harnessing solar heat in the winter. The purpose of this thesis is to apply parametric design and assess the influence of various design conditions or factors at an early design stage. For this study, the physical shape of the atrium is kept with the present case, and only geometrical forms of skylight are taken into consideration. Based on Mat Lab results demonstrating the relationship between the essential elements that fundamentally influence sunshine and visual comfort, the study adopted a mathematical approach to evaluate daylighting performance.This research could be seen as a first step in creating architectural guidelines that aim to give designers a general point of reference when they are deciding on atrium design in the early design stages. Nonetheless, the goal of the research is to offer trustworthy direction based on straightforward measured or calculated inputs. The atrium design and the skylight shape and aperture are the two main factors used to forecast the amount of daylight in atriums in this paper.

Keywords:atrium, daylight factor, skylight, skylight transmittance, illumination

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INTRODUCTION

One of the industries with the fastest increasing energy use is commercial buildings. This is primarily because of how quickly commercial and public activities are developing and how much heating, cooling, and lighting they require. [1]. More emphasis on energy efficiency and architectural prominence may result in airtight and newly insulated building designs. Building system maintenance involves a very complicated design, construction, and control procedure. If everything is done correctly, the finished product functions effectively and affordably while providing comfort, safety, and a healthy atmosphere [2].

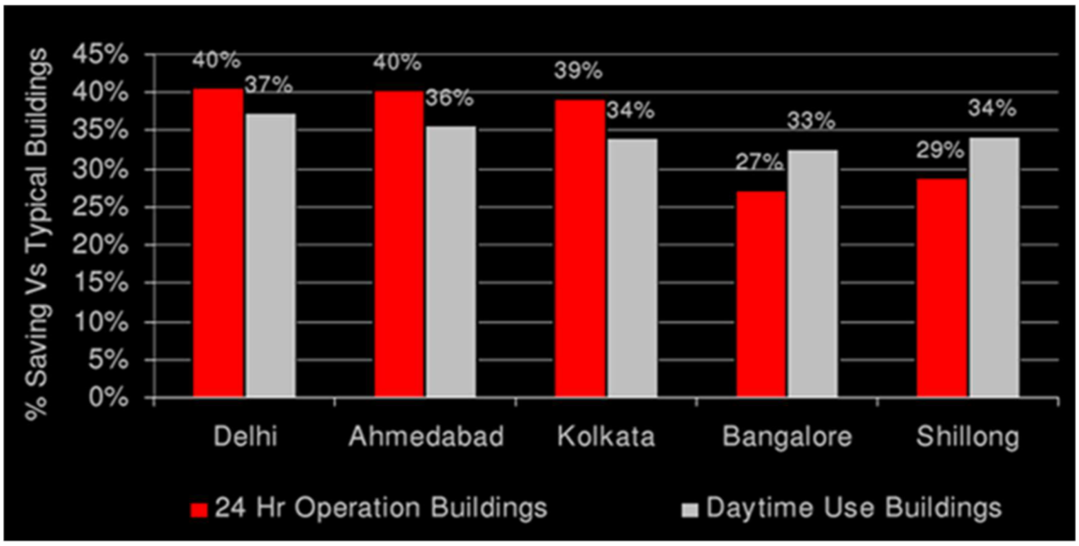

Fig: 1 Energy savings potential between 23 to 46 % was identified
Source: Energy Conservation Building Codes-Overview UNDP-GEF-BEE and EMC Kerala

More intricate issues call for greater focus, which produces a higher caliber solution. Important criteria utilized in the academic study include examining abuilding's thermal comfort and energy performance. The essential components of the atrium that have a significant impact on a building's energy performance have been established by numerous research examining the atrium's energy performance. Atriums have a lot of potential for energy-saving techniques, but these savings cannot be realized without careful research [3]. By providing design parameters for atria to architects at the beginning of a project, time and money can be saved, and the possibility of getting the best outcome is greatly increased. The main objectives of this thesis were to create an atrium that was visually pleasing, had plenty of daylight, and could tell the time.So, the objective of this research is to increase sunshine in atriums while providing visual comfort. The energy savings induced by an atrium arenot achieved without difficulty [3]. For example, it is seen, building users rarely turn off artificial lighting even when daylight is sufficient for visual tasks. The complete integrative design process, supported by calculation models to examine the main component values for maximizing skylight potential daylighting, has a substantial impact on achieving daylight in atrium buildings. Several earlier researchhas supported the advantages and benefits of daylighting, including energy savings, health improvements, and cost savings[4]. Better lighting conditions have been shown to enhance sales by 40% and productivity by 0.7%-23%, according to one study from the Institute for Building Performance and Diagnostics at Carnegie Mellon University[5].The biggest savings come from using less electricity for lights, which reduces internal heat gains and, consequently, the demand for cooling. [6].

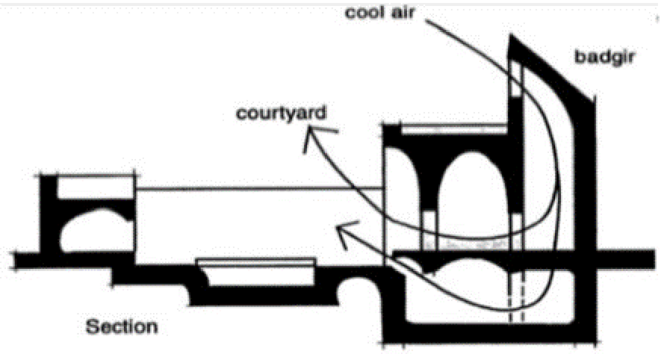

Fig: 2 Section of Typical Persian House with courtyard and wind catcher in the Middle East

Historically, the atrium has been used as a place for increasing light in indoor spaces since the nineteenth century[7]The Roman word "atrium" originally referred to the central court or room with smoke walls. The atrium in a typical old Persian home was the name given to this space. (Fig 2), the coined word in modern architecture now refers to a new form of space with glass walls and a roof that create connected areas throughout the building. It is notified that studies on atriums’ energy performance have started since 1980. For instance, in 1987, the Design for Energy Conservation with Skylights and a Skylight Handbook stated that atrium fenestration might lower energy use for lighting and cooling. [8]. The atrium's shape, glazing, ventilation system, and shading arrangement are some of these components. In assessing factors like thermal comfort, daylighting, air quality, and ventilation based on the building elements, which also include the envelope, orientation, HVAC system, roof aperture, roof transmittance, glazing area, attribution of the adjacent spaces, and atrium type and shape, the interior environmental parameters undoubtedly play important roles[8].

By the late 1800s, cities in developing nations were under pressure to house a rising number of residents, which resulted in higher, more compact building styles. This reduced, and in many cases completely eliminated, the direct view of the sky from much of the usable, interior space. This partially prompted the need for an objective measurement of a space's daylighting performance that might, if necessary, serve as a tool to assess buildings at the planning stage. During that time, daylight was still the favoured source of illumination for both manual labour and office work because it was "free."[9].

BRIEF LITERATURE REVIEW AND PROBLEM FORMULATION

Thermal comfort is one of the comfort issues that is deemed to be the most crucial because it is related to solar radiation and a building's glazing, and air temperature is the most essential influencing element. Glazing is necessary to create daylighting in addition to providing thermal comfort. As a result, it is determined that U-value, solar heat gain coefficient, and light transmission coefficient are the key variables to consider when choosing a glazing material [10].

By including the right energy-efficient components, such as those in the building plan and facade, the overall building design can be improved. Through the use of passive strategies, such as the building's orientation, insulation, glazing, cooling and heating capabilities, reflective glazing, passive solar system, and landscaping, the building's architectural design achieves energy efficiency or cost-effective energy usage. Electrical and mechanical systems are designed using active energy management techniques. [11].

An atrium can thus provide greater connections to interior rooms and draw daylight to both adjacent and internal spaces. The upper floors typically have excessive lighting that makes the spaces uncomfortable to look at, whereas the lower floors don't get enough light [12]. Regarding this concern, CIBSE reported in Lighting Guide 10 [13]that further strategies are required to balance the issues of over lighting on the upper floors and insufficient daylight on the lower floors in atrium building design. As a result, an atrium can improve linkages to interior spaces and bring light into both external and internal areas. The lower floors don't get enough light, while the upper floors frequently have excessive lighting that makes the areas uncomfortable to look at. Furthermore, by reviewing the current daylighting guides, for example, the CIBSE Lighting Guide 10: Daylighting [13] was found to lack information on how to scale up roof glazing, despite including sections about roof light and atriums. Yet grading schemes like Leadership in Energy and Environmental Design (LEED) were first created to offer a framework for evaluating the performance of buildings.

They don't offer advice for making design decisions; they only set a bar for passing or earning credits[14]. Some research explores the complex daylighting performance by computing the findings using mathematical formulae, but the verification of the calculation process is difficult, and the labour is typically enormous (Wong, I.L 2017). A common methodology for assessing daylighting performance at the moment is computer simulation [15]. Computer simulations offer predictions on the performance of a future building at the design stage, despite having drawbacks including issues with the quality of the outcome data [16].Also, this approach has the potential to offer dynamic forecasts, which is particularly helpful when using a parametric design to assess the effects of various design conditions or parameters on building performance. Several daylight measures have been created and deployed throughout the years to assess daylighting performance in terms of daylight quantity and visual comfort (quality)[17].The Daylight Factor is the most popular way for measuring the amount of daylight (DF). It measures the amount of diffuse daylight that is present at various locations within a room when the sky is overcast [18]. However, DF drawbacks like as lack of climate sensitivity, building orientation, and location render it unattractive. The concept of Climate-Based Daylight Modelling (CBDM) was established around 20 years ago. CBDM is defined as the prediction of luminous quantity while considering the variability of sun and sky conditions, which makes it possible to quantify space daylight performance with practical weatherdata [19]. Sustainable building rating system LEED updated its required daylighting-evaluation metric to spatial daylight autonomy (DA) from the fourth version) [14].

To assess visual comfort, discomfort glare probability (DGP) can be used to indicate the level of visual discomfort from glare [20] [21] but the limitations are still noticeable. For example, the calculation of DGP is complex, needing luminance values that are difficult to acquire [22]. Moreover, the calculation has to be based on a specific time point and sky condition [21].The DGP could be calculated annually by some prediction programmes, but this method is time-consuming because it necessitates stopping the ambient computation and redoing the point-in-time calculation for each hour of the year. [21]. DGP's requirement for a specific defined scene (such as a specific observer's position, view direction, and furniture) presents another important barrier from a practical standpoint. This requirement creates significant challenges and difficulties for using DGP in the frame of design and optimization processes[21] and renders it inappropriate in situations where occupants are movable. Furthermore, some research [22] claim that DGP is unreliable in areas with direct sunshine or specular reflection. DGP may not be appropriate, it has been noticed, in practise spaces with numerous reflective materials (like glass) that may undoubtedly generate specular reflection or in situations with significant roof glazing areas where it is impossible to avoid direct sunlight.Furthermore, Dubois and Flodberg [23] used DA max as the indicator of visual comfort risk to investigate the daylighting utilization in perimeter office rooms and the design optimization of the impact elements. Making an effort to balance the problem of atrium daylighting that overlights the top floors but delivers insufficient daylight at lower floors, this study examined the influence of the roof-glazing size of atriums, atrium shapes, and building heights on building daylighting performance, and proposes an intuitional atrium roof-glazing sizing guide for making design decisions at an early stage.

METHODOLOGY

The three primary architectural determinants of an atrium can be understood as generic shapes, dimensional proportions, and fenestration systems[12]. Atriums can be classified into one of four categories, including four-sided, three-sided, two-sided, and linear, according to the taxonomy of the rectilinear form published in the 1980s[5].The basic characteristics of daylighting in atrium space are examined in this study from the literature review. Using data from a field survey, the atrium of a shopping centre was used to measure the amount ofdaylight. The statistical analysis used in this study then applies the mathematical models developed by Laouadi, A.; Atif, M.R. [24] and Perez et al. [25] for the variance in skylight Transmittance Test for different forms of skylight to assess the performances of various skylights.

In Bhopal, the study area is occupied for conducting research. Bhopal, which is in Central India, is becoming a popular destination for FDI (Foreign Direct Investment) investments and is regarded as a major hub for central warehousing. The majority of these changes are located near Bhopal, Indore,

Gwalior, etc. Since the primary centre of the city has more densely packed building types, the Capital Mall, which was repositioned in line with the vision of the new management [26] and the desires of the catchment, was selected as the case study. The roof's opening was circular shape.Moreover, the building's ground floor size was 6587 Sqft, and the atrium's ground floor area had a 110-foot diameter. The atrium well's plan view measurements (length, breadth, or diameter) were 110 Ft in diameter.

Fig: 3 Upper Ground Floor Plan Capital Mall

Fig: 4 First Floor Plan Capital Mall

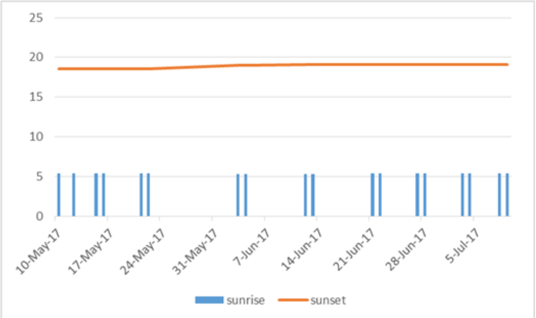

Figure 5 Time Duration (Sun rise and Sunset)

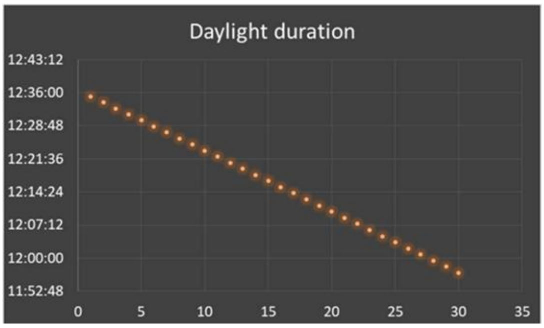

Figure 6: Average Time Duration (Sun rise and Sunset)

Data collection duration began on May 10 and continued until July 9, 2017. Information about the buildings was gathered starting from May 7 until May 11. The field measurement was done for weeks (i.e., May 12 until May 18). The questionnaire surveys were administered during the examination period.

Determining Weather type (i.e., either Overcast or Clear Days)

In this study, a case study with a high ratio catchment was chosen. The weather and cloud patterns as determined at case study locations were observed using a daylight light metre in order to assess the relationship between outdoor and indoor microclimate. Four times a day, at 9:00 a.m., 12:00 p.m., 3:00 p.m., and 5:00 p.m., the sky's condition was checked. An ‘‘Overcast Day’’ was determined based on thin to heavy cloud conditions while a ‘‘Clear Day’’ was resolute based on a clear sky with none to very thin cloud distribution.

Objective Measurements

A number of zones are divided by fake horizontal planes in the area beneath the atrium's skylight. It is assumed that the zone surfaces are flawless diffusers. It is crucial to take the atrium height, illumination fluctuation, and wall reflection into consideration. Each floor was measured at different vertical levels simultaneously. The investigations were conducted in five steps. (1) Lux meters were used for measuring daylight levels for outdoor and indoor purposes. (2) Readings were taken four times a day for each vertical levels zone 1, zone i and zone n. (3) For indoor purposes, the lux meter was located just below the skylight of Atrium and handled 0.8m above the floor. (4) Simultaneously, the second lux meter was mounted 1.5m from the ground in the middle of an open field close to the case study building. (5) Solar Azimuth and Altitude was observed for a particularday to calculate incidence angle of sky illuminance falling on the roof glazing.

This particular angle of incidence would suggest as suitable for determining the user’s visual comfort.

Table 1. Description of questions for visual comfort

No	Question	Day condition/ time	Scale type
1	Define your visual comfort in this mall	Overcast Day	Dark to Bright

	when there is natural lighting during…..		
2	Define your visual comfort in this mall when there is natural lighting during…..	Clear Day	Dark to Bright
3	Is natural lighting alone enough to light this space?	Overcast Day	Inadequate to Adequate
4	Is natural lighting alone enough to light this space?	Clear Day	Inadequate to Adequate
5	Are you comfortable with the natural lighting condition of this space?	None	Dissatisfied to satisfied
6	Can you classify the space brightness during these hours (regardless of any weather condition)	Morning Afternoon Evening	Dark to Bright
7	Are you agree that the skylight serves it purpose in allowing natural light into the Atrium well?	None	Disagree to agree
8	Do you feel the experience glare sensation?	Never to always	Clear Day
9	Do you switch on the artificial lights during the daytime?	Never to always	Clear Day

Subjective Measurements
A questionnaire survey was used to examine subjective factors. The questionnaire was created in order to support the subjects. People in mixed-age groups were approached. Only mall patrons, building workers, and store owners were allowed toparticipate in the sample collection. The description of the visual comfort questions utilised in the questionnaire survey is shown in Table 1.

Daylight Factor Measurements
The Bureau of Indian Standards SP: 41(S&T) specifies (DF 1%=80 lux) as the daylight factor measured:for interiors.
Using a lux metre, the Atrium well's daylight level was estimated. The statistical overview for Daylight Level at three different levels is shown in Table 3 for the locations zone 1, zone I and zone 'n. Overall, the majority of the tested levels revealed daylight factors that complied with the CIBSE's recommended minimum daylight factor[13].

Table 2. Daylight Factor (%) level at three levels: on the Upper Ground Floor, First, and Second floors of Atrium Well as measured:

Daylight Factor		
Upper Ground (zone 1)	First Floor(Zone ‘i’)	Second Floor(Zone ‘n’)
462 lux	564 lux	640 lux

Second Floor, especially when the solar altitude was high was over-lit, namely above 5% of Daylight Level, which exceeds the average daylight factor for public areas [27].

The zone ‘i’ measured daylight factor was lower than the second floor. Comparison of the calculated and measured levels of the Atrium Well is done in order to comprehend daylighting behaviour. As a result, a mathematical analysis of the Daylight Factor was performed under various weather conditions and throughout various daytime hours.
Statistical Analyses

Results from this investigation were examined using Statistical Program for Mathematical Formulation (MAT LAB) version R2012a. The variance skylight transmittance test for various skylight shapes served as the statistical analysis used in this study. A dependent variable's statistically significant impact on another dependent variable is assessed using an inferential statistics test. Different skylight shapes encountered each assessment condition in a repeated measure. By contrasting the tests, this approach can provide information about how to structure and compute variation in assessments more precisely.

Furthermore, it is often useful to know not only whether an experiment has a statistically significant effect, but also the size of any observed effect.

The top ground floor and first floor, which are placed at 4 and 15 metres above the ground, display variance in the daylight level than the top second floor due to the ceiling reflectance and the wall reflectance, according to an observation of daylight level atvarious positions of the atrium well. As anticipated, the ground floor's shadowed region adjacent to the atrium well had the least amount of daylight compared to the adjacent areas on the first and second floors. As a result, atrium forms affect how much daylight is available in the atrium and its surrounding spaces.

In order to quantify the impact of different skylight forms on the interior illuminance distribution on the floor, the skylight transmittance of the present example with a basic segmental dome and translucent material (ideal diffusers) was predicted[24]. The effective transmittance of various skylight shape and type kinds under simulated sky conditions are researched since daylight transmittance of skylights also depends on the sky conditions and the surroundings.

Three types of skies were considered to evaluate the diffuse transmittance of skylights and the average Daylight Factor at the work plane:

1. Isotropic standard overcast skies;
2. CIE standard overcast skies; and
3. Anisotropic skies (Climate-based real skies, which may be overcast, partly-cloudy, or clear). This type is described by the model of Perez et al

Three distinct components are used to evaluate the DF for top-lighting: the sky component (SC), the externally and internally reflected component (ERC), and the internally reflected component (IRC). The aforementioned combines the transmittances of the SC, ERC, and IRC into one equivalent transmittance (eq) and one coefficient of utilisation (CUf), respectively.

CUf: Coefficient similar to the Lumen Method's Coefficient of Utilization (dimensionless) The work plane position, interior surface reflectivity, and atrium geometry all affect the coefficient of utilisation.

Moreover, it can be shown that the Well Efficiency index and the Coefficient of Utilization are identical (WE). By definition, the WE is the ratio of the light flux reaching the base of the well to the incoming flux.

For the Daylight Factor and the Well Efficiency index to be predicted, the Coefficient of Utilization (CU) for the area under the skylight is a crucialmetric. A model is created in the following to calculate each of them for top-lit atriums.

Prediction of the Equivalent Diffuse Transmittance of Skylights

Skylights in atriums receive both direct sunlight from the sky and light reflected from the ground or nearby structures. Laouadi A. and Atif, M.R. provide the equivalent diffuse transmittance for the sum of diffuse light reflected from the sky, ground, and surroundings.

The proportion of radiant radiation radiated by a surface (1) that hits it directly is the conventional definition of view factor (2).

The shapes of the emitter and receiver affect a view factor.
1. Any location on the skylight surface receives diffuse transmission of the incident luminous flux in all directions. Hence, equation (4) is valid for translucent glazing (ideal diffusers), regardless of whether the light source is diffuse (i.e., uniform or not) or direct (from the sun).

2. An inclined flat surface's diffuse transmittance (d) is independent of the angle of inclination. Hence, under a specific sky condition, the diffuse transmittance d can be equivalent to that of a flat horizontal surface (i.e., there corresponds a different diffuse transmittance for uniform and non-uniform sky conditions). If not, the diffuse transmittance d can be thought of as the average overall inclination angles for a certain sky condition.

To carry out the integration across a representative shape, a concept has been devised. (Laouadi A, and Atif MR) A shape parameter transforms the skylight shape into the representative shape. As long as the shape parameter is known, the representative shape can be chosen at random. The truncation angle of '0' is used as the shape parameter, and the dome shape is regarded as the typical shapea zone number and the coefficients with θ the incidence angle on a tilted surface and θz the sun zenith angle.

Table 3. Comparative table of Daylight Factor (%) level at three levels: on the Upper Ground Floor, First, and Second floors of Atrium Well as measured and Calculated:

Daylight Factor					
Upper Ground (zone 1)		**First Floor(Zone 'i')**		**Second Floor(Zone 'n')**	
Measured (Lux)	Calculated (%)	Measured (Lux)	Calculated (%)	Measured (Lux)	Calculated (%)
462	5.82	560	6.9	640	8.66

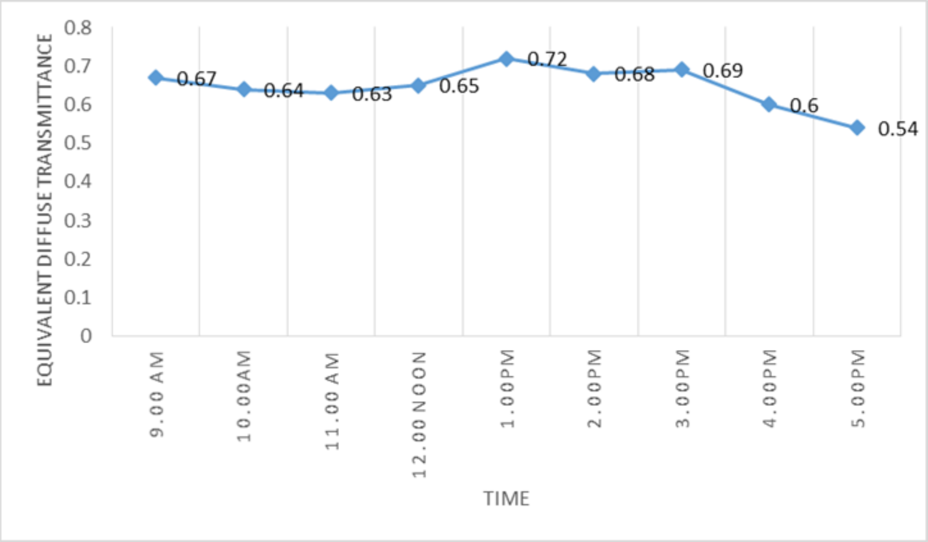

Fig:7 Profile of the equivalent diffuse transmittance during a summer day June 2016

Real sky circumstances are described by Perez et almodel .'s as a superposition of three elements: circumsolar brightening, horizon brightening, and a backdrop isotropic sky. Depending on the local climate and weather, the sky could be anything from overcast to partially cloudy to clear. Based on meteorological information, the coefficients F1 and F2 are estimated. The coefficients F1 and F2 are both zero for isotropic clouds. The coefficient F1 approaches to zero under cloudy sky.

The outdoor horizontal global and diffuse illuminances (Egh, Edh) in equation (10) may be estimated from irradiance values using the model of Perez et al.

Equations (8) for uniform overcast skies and equation (9) for CIE overcast skies both apply to any type of skylights without any restrictions, according to a comparison of the exact values of the equivalent transmittance obtained using the direct evaluation of the incident flux ratio d for different skylight shapes (dome, pyramid, vault, and pitched).

Coefficient of Utilization

The inner surfaces of the atrium are assumed by the zonal model to be ideal diffusers. Also, it is assumed that the skylight is an ideal source of illumination. When a skylight's material is translucent, this restriction is applicable. The sky's conditions will affect the skylight's transmittance, but they won't have an impact on how the flux is distributed inside the atrium because the sky isn't immediately visible from a specific surface's point of reference. In order to replicate different sky conditions (overcast, partially cloudy, and clear), where the index I denotesa zone numberand the coefficients.

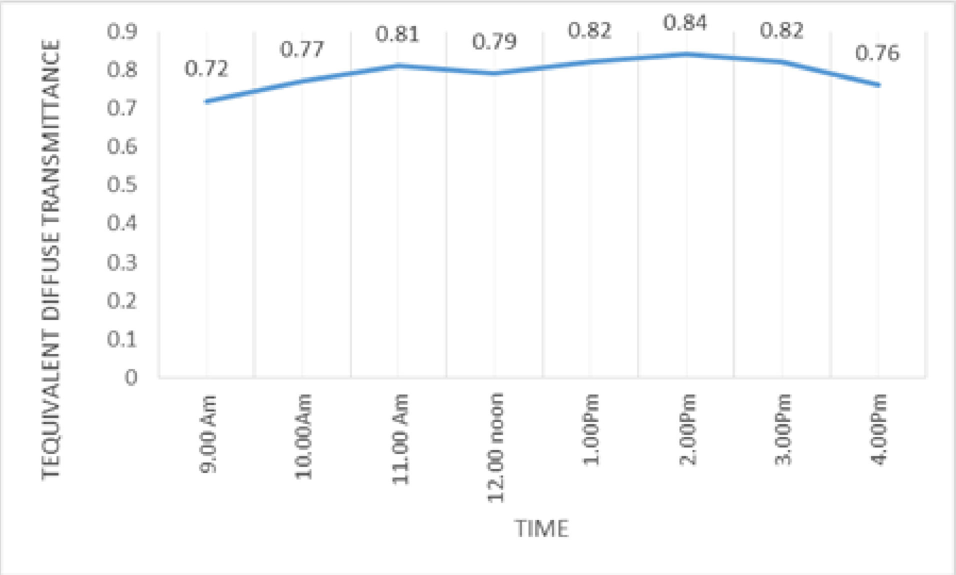

Fig: 8 Profile of the equivalent diffuse transmittance during a summer day Dec 2016

The zone-specific method makes the implicit assumption that the imaginary plane that divides two real surfaces would radiate the same amount of light energy to the real surface on one side as it would receive from the real surface on the other. This implicit presumption is expressed as follows for two real surfaces (A and B) separated by n fictional planes:
The zonal technique will underestimate the DF at floor level in tall spaces because of light loss and overestimate the DF normal to walls because of light gain. Hence, for tall atriums, compute the DF at floor level using the direct technique that does not involve imaginary planes.

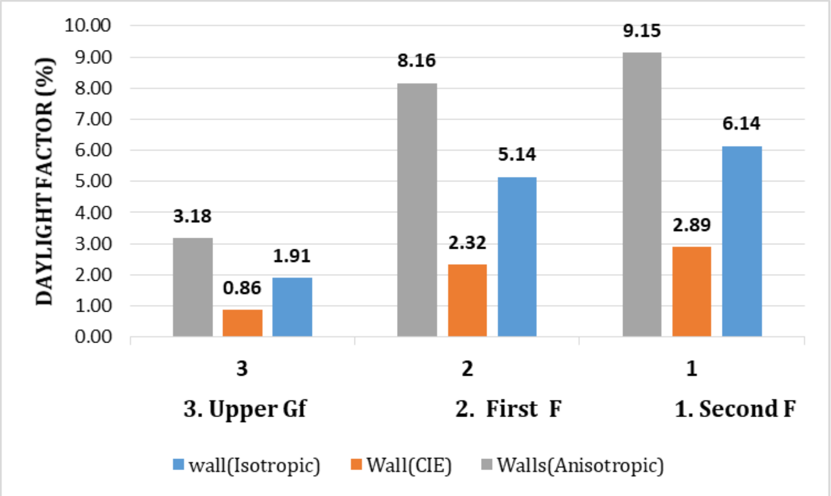

Fig: 9 Comparison chart of three sky conditions.

CONCLUSIONS

The experiment test demonstrates that dome shapes have significantly higher skylight transmittance than other geometric shapes. In this case study, the atrium is equipped with sensors to collect data on the air quality, temperature, and daylight levels. Observations are made, and the subjective analysis is also recorded.

The Daylight visualizer model is then seeded with data from recorded surface temperatures. A number of various sky circumstances are tested throughsimulations, and it is demonstrated that the computer simulation closely resembles the actual conditions. The same settings are tested mathematically as well, and the findings show a noticeable increase in daylight levels.

From the discussions above, some guidelines for supporting daylighting design in atria are the following:

(1) Atrium proportions WI should not be greater than 2 in case of the rectangular atrium. It is already found in a study that a good result can be achieved by WI=1.5 to 2. This study also supports that. (Jiangtao Du, Steve Sharples 2009)
(2) From field survey and simulation result it is seen that reflectance values of the floor have a great impact on daylight level rise.
(3) Ground floor elevation contributes daylight level rise in the upper floor due to floor reflectance.
(4) The Dome shape (Capital Mall) performs better than the Flat, Pitched, Vault, and Pyramid shapes in skylight shapes. This work should be linked to research on the directionality of sunlight coming via skylights.

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