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The Daylight Performance of an Integrated Skylight and Shading Dome for the Tropics

Sopa Visitsak[1], **Liliana O. Beltran**[2] **and Nattaree Sridaranon**[1]

[1] Department of Building Innovation, Faculty of Architecture, Kasetsart University, Bangkok (Thailand)

[2] Department of Architecture, College of Architecture, Texas A&M University, College Station (USA)

Abstract

This paper evaluates the daylighting performance of an integrated skylight and shading dome with natural ventilation (SDV) for residential buildings in the tropics using the RADIANCE lighting simulation program and the Energy Plus Weather (EPW) file for Bangkok, Thailand. Indoor illuminance levels at work plane height of a simulation model with the SDV was compared to that of from similar physical scale model located in natural environment. A typical unit base case model (1.35 m x 1.35 m x 2.80 m) with a circular translucent opening (60% transmittance, r = 0.175 m) was developed to relate with sizing of available conventional roofing materials and typical residence room's height. Daylighting performance of the base case based on Daylight Autonomy (DA 300 lux) was compared to the original SDV and the modified SDVs, which the skylight plate replaced with different translucent materials (40%, 50%, and 60% transmittance). The results show that the modified SDVs' DA are all above 50%. Four typical units of the modified SVD (60% transmittance) were developed to represent an application and compare to a conventional translucent sheet in an extended residence area. The results confirm that the modified SDV has better daylighting quality than the translucent sheet which has similar opening area and light transmittance value (60%). With proper design and material selection, the modified SDV (60% transmittance) could significantly reduce direct sunlight, which is the cause of glare and heat problems for buildings in tropical climates.

Keywords: Daylight simulation, Radiance, Building innovation, Green technology, Sustainable architecture

1. Introduction

In Thailand, most indoor spaces in low rise buildings (e.g. single house, row house, townhouse, etc.) have low daylight levels. Using electric lighting is costly and not a sustainable solution. Conventional translucent sheets have been widely used but it is difficult to control the quality of daylight and always be a cause of significance problems such as heat, glare, and ultra violet, which may be harmful to eyes, artworks, and furniture. Although many products were developed for the use of natural light such as typical transparent and translucent roof sheets with optional of external or internal shading devices. There are limitations of thermal resistance and quality of daylight. Advanced materials and advanced technology devices such as glass reinforced polyester, insulated glass, double panes, low-e coating, laminated glass with a polymer dispersed liquid crystal (PDLC), hyperboloid skylights, dome skylights, tubular daylighting devices, with and without sun tracker and reflective materials have been developed to improve the daylighting performance and thermal insulation. However, the cost of those materials and products are expensive and may not be cost effective.

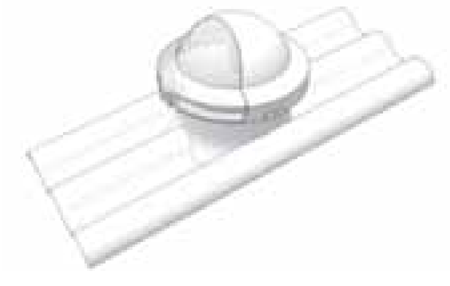

Fig. 1: An integrated skylight and shading dome with natural ventilation (SDV)

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We are proposing an integrated skylight and shading dome with natural ventilation (SDV) (Fig.1), which was developed from the previous one (without natural ventilation system) (Visitsak et al., 2014) as a sustainable solution that could reduce significantly problems of heat, glare, and ultra violet. The opening and the shading form were developed to responds to sunpath (Stein and Reynolds, 2000) for Bangkok, Thailand (latitude 13.76° N, longitude 100.52° E) in order to protect direct light (100%) throughout the year. The design also allows building occupants to perceive external view through the opening and be connected with the environment.

The objective of this paper is to evaluate the daylighting performance of the SDVs (original and modified) and typical translucent skylight using the RADIANCE lighting simulation program (Ward, 1996), which was found to be the most generally useful software package for architectural lighting simulation program (Reinhart and Fitz, 2006) as well as a highly optimized daylighting and energy modeling plug-in, DIVA-for-Rhino (v.4).

2. Methodology

The SDV consists of two main parts: 1) a circular metal skylight plate (r = 0.175 m, area = 0.096 m^2,) on a metal tube (height = 0.185m) with an opening area to allow only indirect sunlight and the opaque area to obstruct direct sunlight and 2) a transparent acrylic dome (88% transmittance), which the shading area for protecting direct sunlight is silver painted. The reflectance values of ceiling, walls, and floor are 70%, 70% and 20%, respectively. The process of conducting and comparing daylight performance of the original and modified SDVs and typical translucent skylight using simulation and Bangkok weather comprised 3 steps:

2.1. Calibration of simulation model (original SDV)

A physical scale model with the original skylight and shading dome (SDV) installed on the roof (Fig.2) was prepared and tested outdoor in Ayuthaya, Thailand (latitude 14.37° N, longitude 100.59° E). The model dimensions were 1.00 m wide x 1.00 m long x 2.30 m high. Indoor illuminance at work plane (0.80 m) on March 6th at noon, when the outdoor illuminance was similar to that of from Bangkok weather data (EPW), was used to calibrate with the results of simulation model using Bangkok weather data from Energy Plus Weather file (DOE, 2017).

(a) (b) (c)

Fig. 2: Simulation model of the skylight and shading dome (SDV): (a) Plan (b) Section and (c) Perspective

2.2. Daylighting performance: One unit (base case, original SDV, and modified SDVs)

A typical unit base case model with dimensions 1.35 m wide x 1.35 m long x 2.80 m high and a circular opening equivalent to the SDV's circular skylight plate (r = 0.175 m, area = 0.096 m^2) was developed to relate with sizing of available typical roofing materials and typical residence room's height. The daylighting performance at work plane (0.76 m) based on daylight autonomy (300 lux) during the occupied hours (8:00 a.m.-6:00 p.m.) throughout the year (Reinhart et al., 2006) of the base case with a circular translucent opening (60% transmittance) (Fig.3a) was compared to that of from the original SDV and modified SDVs, which the skylight plate (opaque part) was replaced with an alternative translucent material with different transmittance (40%, 50%, and 60%) (Fig.3b).

(a) (b)

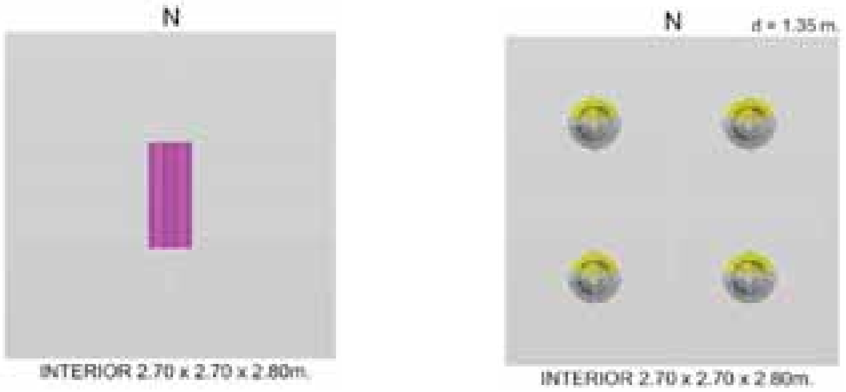
Fig. 3: Simulation model: One unit (a) Base case (Circular translucent material, $\tau = 60\%$) (b) Original SDV & Modified SDVs ($\tau = 40\%$, 50%, and 60%)

2.3. Daylighting performance: Four units (translucent sheet vs. modified SDVs)

Four typical units with dimensions 2.70 m wide x 2.70 m long x 2.80 m high represent an application of a conventional translucent sheet (opening area = 0.38 m^2, 60% transmittance) in an extended residence area with typical cement roof sheets. The daylighting performance at work plane (0.76 m) of the translucent sheet installed on the roof (Fig.4a) based on Daylight Autonomy (DA300 lux), which represents percentage of annual daytime hours during the occupied hours (8:00 a.m.-6:00 p.m.) that a given point in the area is above 300 lux, was simulated and compared with the results from four modified SDVs (Fig.4b) with 40%, 50%, and 60% transmittance, which have equal opening area and placed 1.35m apart from each other, installed on roof.

The best modified SDV option (60% transmittance) from the previous step was used to simulate and compare daylighting performance results to the translucent sheet. The daylighting performance results include mean indoor illuminance on the summer solstices (Jun 21st at noon) when the external daylight is critical and mean Useful Daylight Illuminance that indicates percentage of occupied hours per year when daylight illuminance falls within a range from 300-3000 lux (UDI 300-3000 lux) (Nabil and Mardaljevic, 2005; 2006), as well as the daylighting metrics in LEED v4, which are Spatial Daylight Autonomy (sDA300/50%) (IESNA, 2012) that indicate percentage of the area that meets or exceeds 300 lux at least 50% of the occupied hours per year, and Annual Sun Exposer (ASE1000/250) (IESNA, 2012) that identified potential of discomfort and should be no more than 10% of the area exposed to direct sunlight more than 1000 lux for 250 hours per year.

In addition, simulation glare images for sitting eye level from the corner of the room for the translucent sheet and the best modified SDV (60% transmittance) as well as glare indices results of Daylight Glare Probability Index (DGP) (Wienold and Christoffersen, 2006), Daylight Glare Index (DGI) (Hopkinson, 1972), Unified Glare Index (UGR) (CIE, 1992), Visual Comfort Probability Index (VCP) (IESNA, 1993) and CGI/CIE Glare Index (Einhorn, 1969) on the four representative dates (Mar 21st, Jun 21st, Sep 21st, and Dec 21st) at noon were also simulated and compared.



(a) (b)

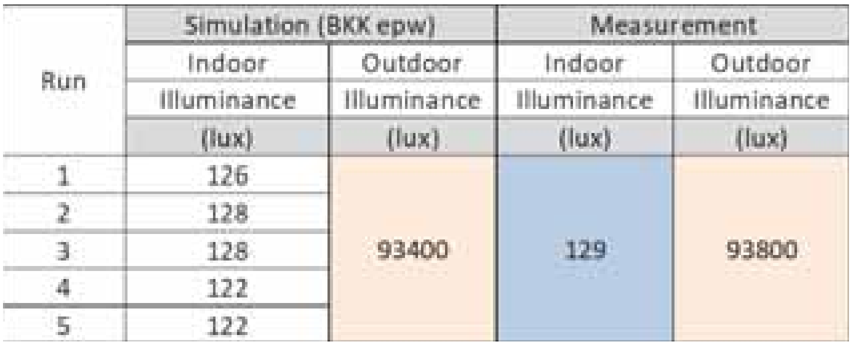
Fig. 4: Simulation model: Four units (a) Translucent sheet ($\tau = 40\%$), (b) Modified SDVs ($\tau = 40\%$, 50%, and 60%)

3. Data analysis and results

3.1. Calibration of simulation model (original SDV) results

The indoor illuminance at work plane (0.80 m) of the physical scale model with the original skylight and shading dome (SDV) installed on the roof, which was located in Ayutthaya, (March 6, at noon) was used to calibrate with the results of simulation model using Bangkok weather file (March 6, at noon). Table 1 shows that the average indoor illuminance (125 lux) from simulation model, when the outdoor illuminance from Bangkok weather file (93,400 lux) is similar to the outdoor illuminance from field measurement (93,800 lux), corresponds to the indoor illuminance (129 lux) measured from the physical scale model. The results confirm that the simulation model is compatible with the physical scale model and could be used to modify and simulate daylighting performance of various conditions in the next step.

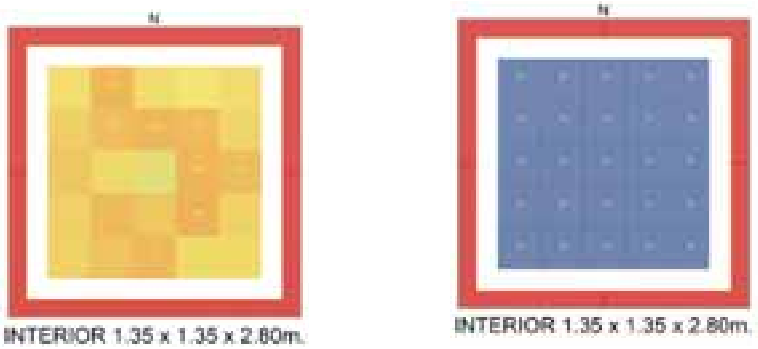
Tab. 1: Comparison of indoor and outdoor illuminance from simulations and field measurements (Mar 6, at noon)



Run	Simulation (BKK epw)		Measurement	
	Indoor Illuminance (lux)	Outdoor Illuminance (lux)	Indoor Illuminance (lux)	Outdoor Illuminance (lux)
1	126	93400	129	93800
2	128			
3	128			
4	122			
5	122			

3.2. Daylighting performance results: One unit (base case, original SDV & modified SDVs)

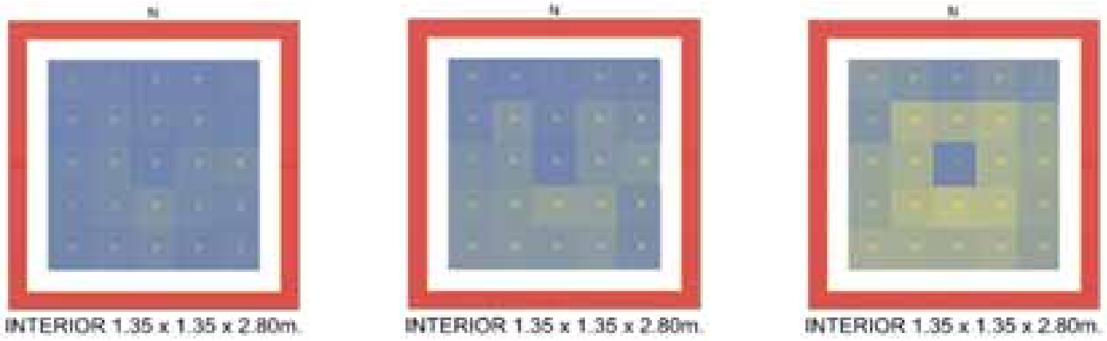
The simulation results of one unit (1.35 m wide x 1.35 m long x 2.80 m high) in Figs. 5 & 6 show Daylight Autonomy (300 lux) during the occupied hours (8:00 a.m.-6:00 p.m.) of the base case model with a circular translucent material (60% transmittance), the original SDV, and the modified SDVs, which the skylight plate (opaque part) was replaced with translucent material with different transmittance (40%, 50%, and 60%). As expected, the percentage of DA (300 lux) increases with the transmittance value. The percentages of DA (300 lux) of the original SDV and the modified SDVs (40%, 50% and 60% transmittance) are 0%, 2.44%, 6.72%, and 16.76%, respectively. Although they are all lower than that of the base case (60.4%), an alternative translucent material with different transmittance (40%, 50% and 60%) is effective and increases the percentage of Daylight Autonomy.



Base case: Circular translucent material (τ = 60%) (DA = 60.4%)

Original SDV (DA= 0%)

Fig. 5: Percentage of DA (300 lux) of one unit: Base case (Circular translucent material, τ = 60%) and Original SDV



Modified SDV (τ= 40%) Modified SDV (τ= 50%) Modified SDV (τ= 60%)

(DA= 2.44%) (DA= 6.72%) (DA= 16.76%)

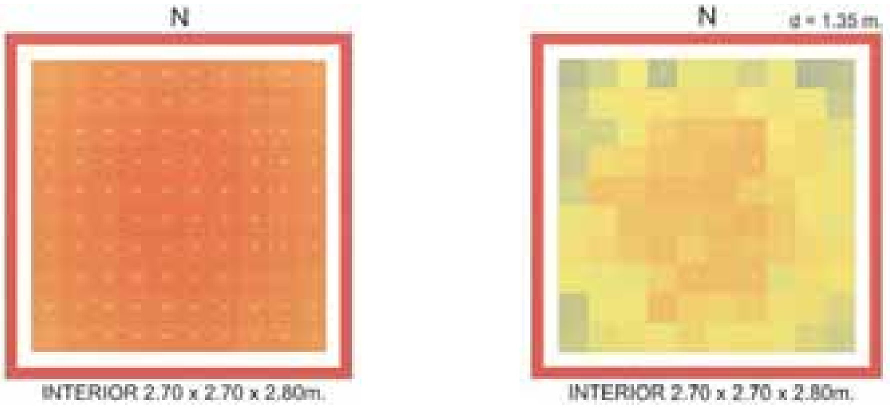
Fig. 6: Percentage of DA (300 lux) of one unit: Modified SDVs (τ= 40%, 50%, and 60%)

3.3. Daylighting performance results: Four units (translucent sheet vs. modified SDVs)

- *Daylight Autonomy (300 lux) results:*

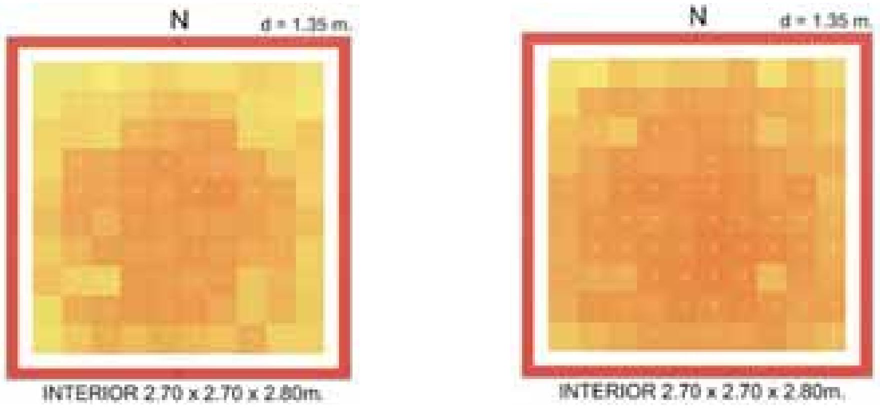
In Fig.7, the results show that the percentages of Daylight Autonomy (300 lux) during the occupied hours (8:00 a.m.-6:00 p.m.) corresponds to the DA (300 lux) results in Figs. 5 & 6, which increase with the transmittance value. In addition they also increase with larger space for all cases. The percentages of DA (300 lux) of four units of the conventional translucent sheet (60% transmittance) and the modified SDVs (40%, 50% and 60% transmittance) increase to 86.57%, 52.64%, 66.3%, and 73.57%, respectively. Although the modified SDVs (40%, 50%, and 60% transmittance) have percentage of DA (300 lux) lower than that of the translucent sheet (60% transmittance), they are all above 50% DA (300 lux).

Translucent sheet (τ= 60%) Modified SDV (τ= 40%)



(DA = 86.57%) (DA = 52.64%)

Modified SDV (τ= 50%) Modified SDV (τ= 60%)

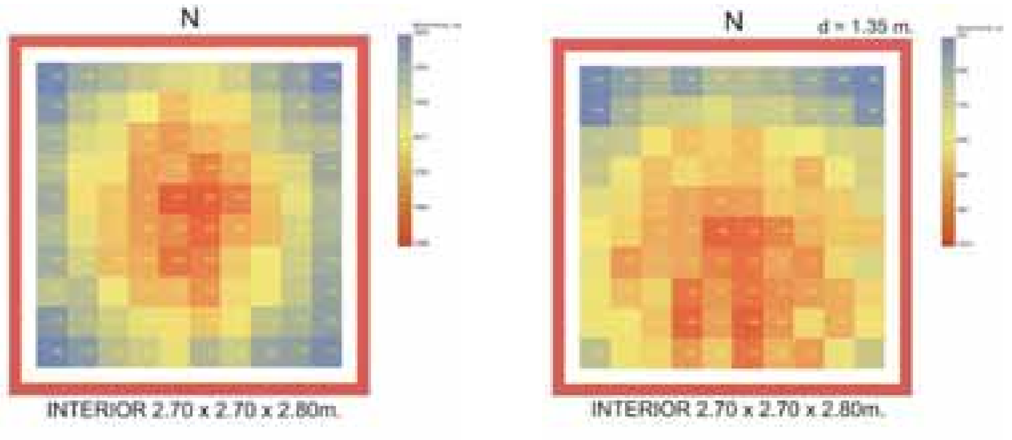


(DA = 66.3%) (DA = 73.57%)

Fig. 7: Percentages of DA (300 lux) of four unit: Translucent sheet (τ= 60%) vs. Modified SDVs (τ= 40%, 50%, and 60%)

- *Mean illuminance results:*

Fig. 8 shows the results of mean illuminance on the June 21st (at noon) of the translucent sheet and the modified SDV with similar transmittance value (60%). Mean illuminance on the June 21st (at noon) of the translucent sheet is 1551 lux with illuminance level ranging between 1074-2148 lux for 98% of the area, which is much higher than the standard indoor illuminance requirements and that of the modified SDV with 60% transmittance. The mean illuminance of the modified SDV (60% transmittance) is 831 lux with illuminance level ranging between 537-1074 lux for 97% of the area. The results implies that the modified SDVs in larger space could provide sufficient daylighting and reduce incoming solar radiation significantly.


Translucent sheet ($\tau = 60\%$)

Modified SDV ($\tau = 60\%$)

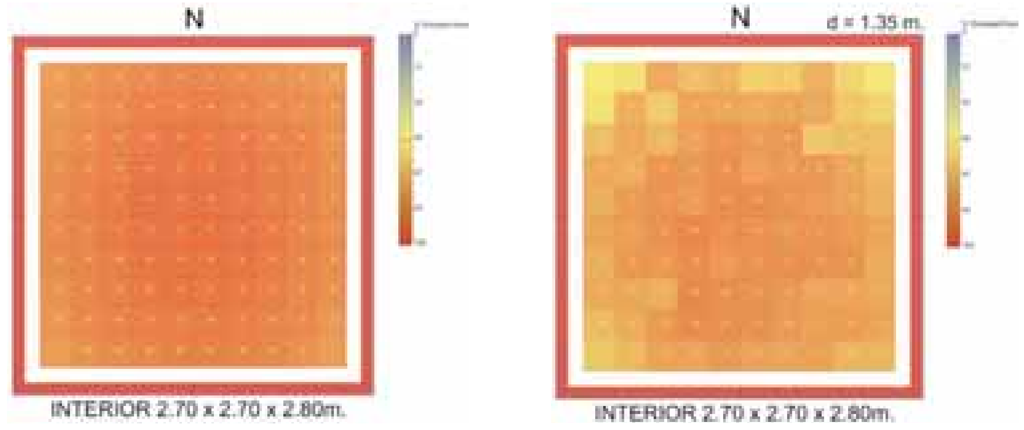
98% of area (1074-2148 lux)
Mean illuminance 1551 lux

97% of area (537-1074 lux)
Mean illuminance 831 lux

Fig. 8: Mean Illuminance of four units, Jun 21st at noon: Translucent sheet ($\tau = 60\%$) vs. Modified SDV ($\tau = 60\%$)

- *Mean Useful Daylight Illuminance (UDI 300-3000 lux) results:*

Simulation results in Fig.9 indicate percentages of occupied hours per year when daylight illuminance falls within a range from 300-3000 lux (UDI 300-3000 lux). For the translucent sheet (60% transmittance), there are 77% to 93% of the occupied hours per year that the partial areas have illuminance in the range from 300-3000 lux and the mean UDI (300-3000 lux) equals to 86.46%. The UDI (300-3000 lux) of the modified SDV (60% transmittance) vary from 50% to 85% and mean UDI (300-3000 lux) is 73.99%. UDI (300-3000 lux) of both cases are higher in the middle of the areas and spread out to lower value in the perimeters and in the corners of the areas.


Translucent sheet ($\tau = 60\%$)

Modified SDV ($\tau = 60\%$)

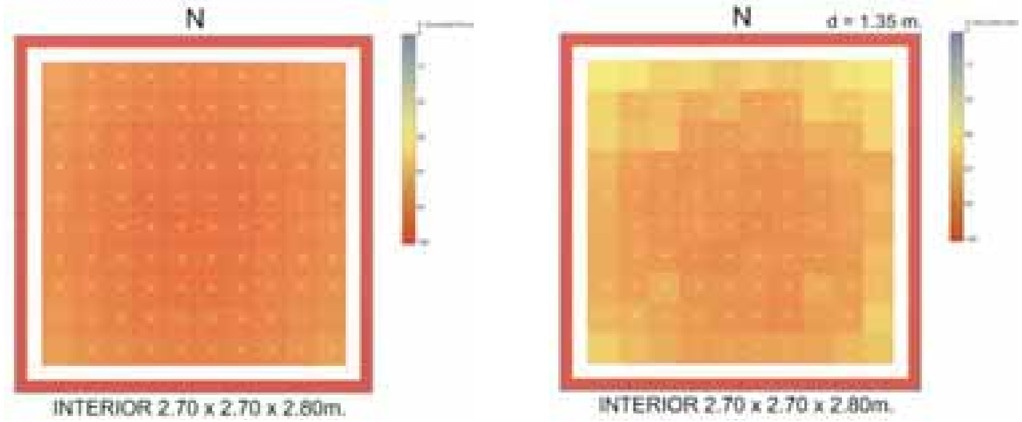
Mean UDI (300-3000 lux) 86.46%

Mean UDI (300-3000 lux) 73.99%

Fig. 9: Mean Useful Daylight Illuminance (UDI 300-3000 lux) of four units: Translucent sheet ($\tau = 60\%$) vs. Modified SDV ($\tau = 60\%$)

- *Spatial Daylight Autonomy (sDA300/50%) and ASE (1000/250) results :*

In Fig.10, the simulation results show that 100% the translucent sheet (60% transmittance) room area and 98% of the modified SDV (60% transmittance) room area have a *Spatial Daylight Autonomy* at 300 lux value for more than 50% of the occupied hours. For both cases, none of the areas are exposed to direct sunlight more than 1000 lux for 250 hours per year, which qualify for 3 LEED points in LEED v4.


Translucent sheet ($\tau = 60\%$)

Modified SDV ($\tau = 60\%$)

sDA (300/50%) 100%, ASE (1000/250) 0%

sDA (300/50%) 98%, ASE (1000/250) 0%

Fig. 10: Spatial Daylight (sDA 300/50%): Translucent sheet and Modified SDV ($\tau = 60\%$)

- *Glare Evaluations (DGP, DGI, UGR, VCP, CGI)*

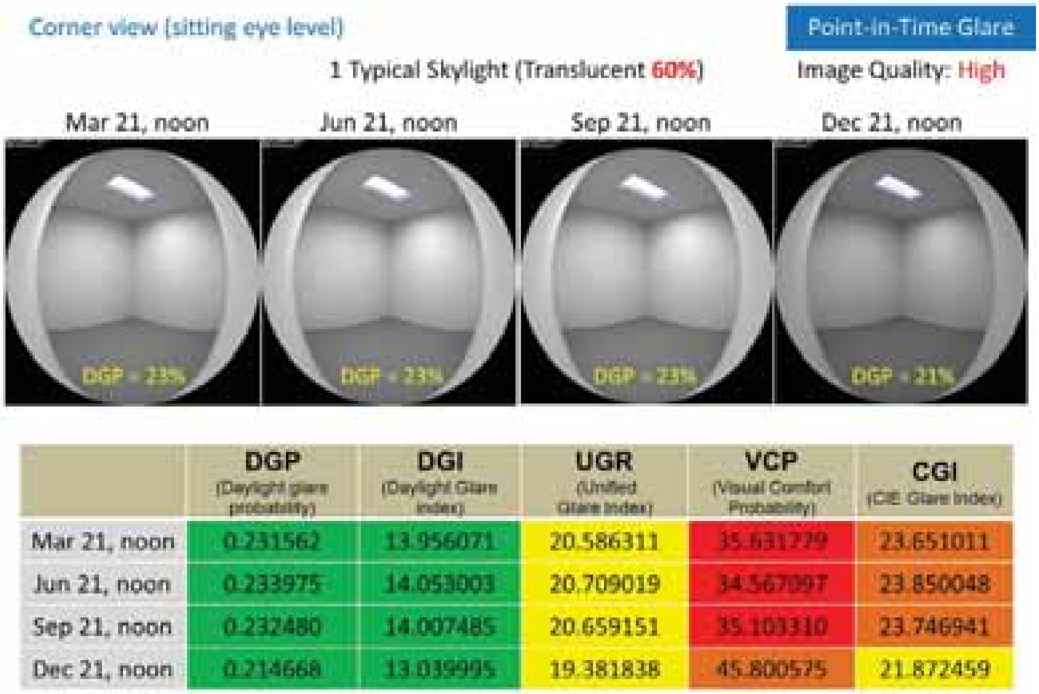
In (Figs.11-12), the simulation glare images and glare indices *(DGP, DGI, UGR, VCP, CGI)* for sitting eye level from the corner of the room on Mar 21 st st, Jun 21 st st, Sep 21 st st, and Dec 21st (at noon) are presented. Green, Yellow, Orange, and Red colors that correspond to glare value ranges represent the levels of glare, which are imperceptible, perceptible, disturbing, and intolerable, respectively.

The results show that the glare value ranges of Daylight Glare Probability Index (DGP) and Daylight Glare Index (DGI) on all selected dates for the conventional translucent sheet (60% transmittance) and the modified SDV (60% transmittance) are imperceptible glare. Base case has higher DGP glare values and lower DGI glare values than the modified SDV, except on Dec 21st.

The results are different for Unified Glare Index (UGR), Visual Comfort Probability Index (VCP) and CGI/CIE Glare Index, which in general the modified SDV has better glare values than the translucent sheet (60% transmittance) for all selected dates. It implies that the modified SDV (60% transmittance) has less glare problems than the base case, especially on Dec 21st when the sun ray is lower. For base case, the results show significant problem of intolerable glare on Mar 21st , Jun 21st , and Sep 21st as well as disturbing glare on Dec 21st for the Visual Comfort Probability Index (VCP).

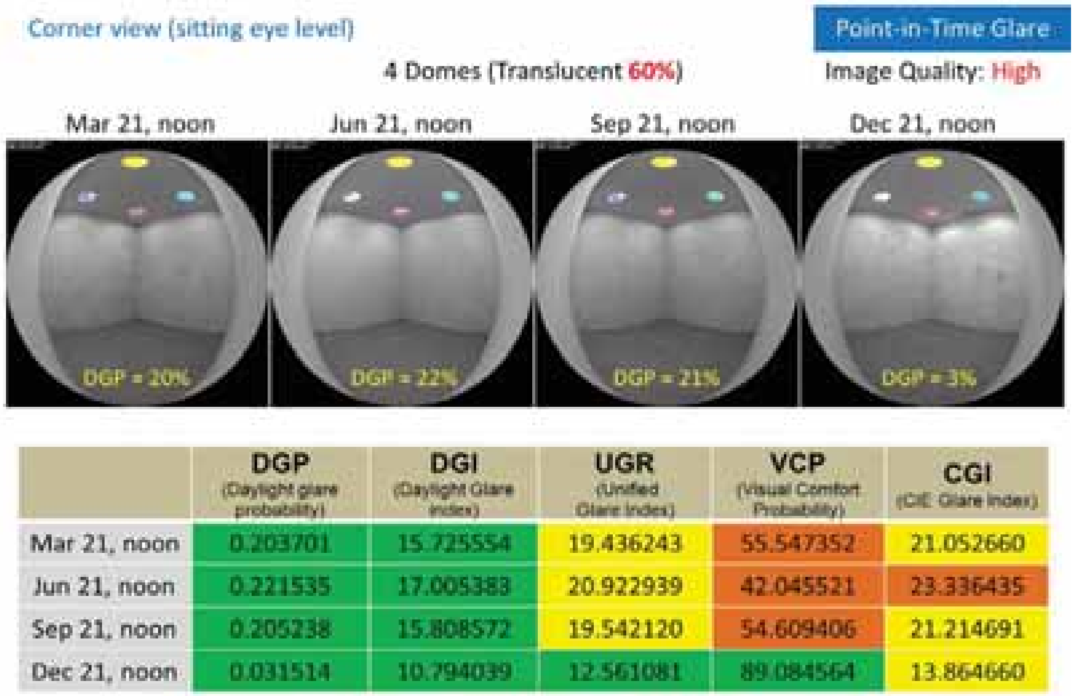
4. Conclusion

Daylighting performance of an integrated skylight and shading dome with natural ventilation (SDV) for the tropics and alternative materials were investigated using the RADIANCE lighting simulation program and the weather file (EPW) for Bangkok, Thailand. The daylighting simulation results show that, with proper design and material selections, the daylighting performance of the modified SDVs with part of the skylight plate replaced with an alternative translucent materials (40%, 50%, and 60% transmittance) are above 50% daylight autonomy (300 lux). The modified SVD with 60% transmittance provides appropriate indoor illuminance with mean UDI 73.99% of occupied hours in the range of 300-3000 lux as well as 98% of the area have a *Spatial Daylight Autonomy* at 300 lux value for more than 50% of the occupied hours without any of the areas are exposed to direct sunlight more than 1000 lux for 250 hours per year, which qualify for 3 LEED points. The modified SVD (60% transmittance) has better daylighting quality than a conventional translucent skylight with similar opening area and light transmittance value (60%). In addition, the modified SDVs could reduce glare problems and incoming solar radiation that exceeds indoor illuminance requirements, which is the cause of heat problem for buildings in tropical climates.



	DGP (Daylight glare probability)	DGI (Daylight Glare index)	UGR (Unified Glare Index)	VCP (Visual Comfort Probability)	CGI (CIE Glare Index)
Mar 21, noon	0.231562	13.956071	20.586311	35.631779	23.651011
Jun 21, noon	0.233975	14.053003	20.709019	34.567097	23.850048
Sep 21, noon	0.232480	14.007485	20.659151	35.103310	23.746941
Dec 21, noon	0.214668	13.039995	19.381838	45.800575	21.872459

Fig. 11: Glare evaluations: Translucent sheet ($\tau = 60\%$)



	DGP (Daylight glare probability)	DGI (Daylight Glare index)	UGR (Unified Glare Index)	VCP (Visual Comfort Probability)	CGI (CIE Glare Index)
Mar 21, noon	0.203701	15.725554	19.436243	55.547352	21.052660
Jun 21, noon	0.221535	17.005383	20.922939	42.045521	23.336435
Sep 21, noon	0.205238	15.808572	19.542120	54.609406	21.214691
Dec 21, noon	0.031514	10.794039	12.561081	89.084564	13.864660

Fig. 12: Glare evaluations: Modified SDV ($\tau = 60\%$)

5. Acknowledgement

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