Title

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Authors
Szu-Cheng, CHIEN
King Jet, TSENG

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Evaluation of Climate-Based Daylight Performance in Tropical Office Buildings- A Case Study

CHIEN Szu-cheng[1,2,*], Tseng K.J.[3]

[1] Berkeley Education Alliance for Research in Singapore (BEARS) center, CREATE Tower @University Town, NUS, 1 Create Way, #11-01, Singapore

[2] Energy Research Institute, Nanyang Technological University, Clean Tech One, 1 Cleantech Loop, #06-09, Singapore

[3] School of Electrical & Electronic Engineering, Nanyang Technological University, Block S2.1, 50 Nanyang Avenue, Singapore

Corresponding email: scchien@ntu.edu.sg

ABSTRACT

The utilization of daylight can significantly affect building performance, energy efficiency, productivity, as well as occupants' comfort and satisfaction in buildings. This paper aims to assess daylight performance for tropical office buildings in a parametric approach. Thus, four passive design categories are investigated, namely interior surface reflectance, glazing visual transmittance, light shelves, and shading control. We first evaluated the daylight performance metrics, namely daylight autonomy, continuous daylight autonomy, and daylight autonomy max. Subsequently, a parametric approach toward assessing daylight performance is presented. The approach is exemplified using the case study of two selected offices in CREATE Tower, an air-conditioned office building in Singapore. The simulation results were generated based on above-mentioned four categories and then compared. This study contributed to the assessment of the daylight performance and prediction of the consequences of retrofitting alternatives toward fostering the utilization of daylight in existing buildings in the tropics. Furthermore, the outcomes of this effort are expected to serve as a solid basis towards a simulation-based daylight responsive building systems control demonstration in lighting and shading domain.

KEYWORDS: *daylighting, performance simulation, passive design strategies, office buildings, Tropics*

1 INTRODUCTION

Lighting accounts for 20% of energy use in Singapore's office buildings, making it one of the primary energy loads in the building sector, and a critical factor in design strategy for effectively improving office building energy efficiency. To achieve a higher level of energy efficiency and sustainability in the buildings sector, the consideration of natural daylight utilization during the daytime is crucial. Towards this end, the electric lighting would then be supplemental, such that significant reduction of electric lighting demands can be achieved. That can result in significant impacts on building performance, energy efficiency, productivity, as well as occupants' comfort and satisfaction. Nowadays, the most used daylight metric is based on simplified daylight performance model at one time step under the standardized overcast sky. There have been concerns that the results obtained from such metric may not reflect intermediate daylight performance conditions over an extended period of time with variable sky conditions. In recent years, a number of more elaborate daylight metrics have been proposed [1,2,3]. In this context, our research effort describes a systematic approach toward obtaining and assessing simulation-based daylight performance data from high-rise office buildings.

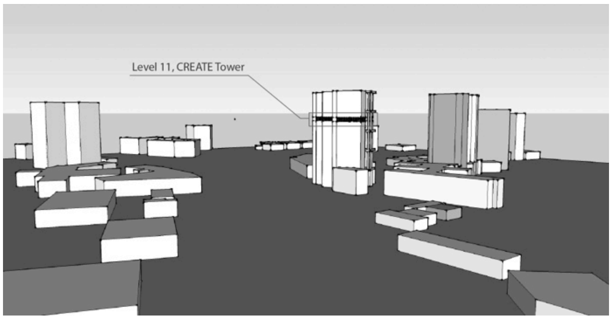
This approach is currently being applied within the framework of a living lab project, under the purview of the Singapore-Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST) Program. Thereby, amongst other activities, local climate and building performance (involving visual/ thermal performance and occupancy) data are being collected for this selected living lab in CREATE Tower, a high-rise office building in Singapore. The high-level goal of this living lab research effort is a comprehensive understanding of visual performance in tropical built environment, including the utilization of daylight, energy efficiency, occupant comforts, and integrated intelligent lighting and shading controls.

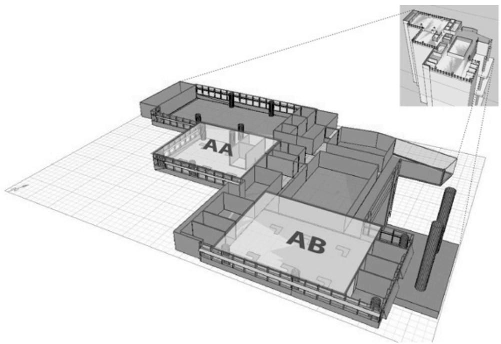
This paper presents a preliminary assessment of daylight performance for tropical office buildings in a parametric approach. Thus, four passive design categories are considered, namely interior surface reflectance, glazing visual transmittance, light shelves, and shading control actions. We first evaluated an array of daylight performance metrics, namely daylight autonomy, continuous daylight autonomy, and daylight autonomy max. Subsequently, a parametric approach toward assessing daylight performance is presented. The approach is exemplified using the case study of two selected offices in CREATE Tower, an air-conditioned office building located in Singapore. Thereby, the simulation results were generated based on above-mentioned four categories and then compared. This study contributed to the assessment of the daylight performance and prediction of the consequences of retrofitting alternatives toward fostering the utilization of daylight in existing buildings in the tropics. Furthermore, the outcomes of this effort are expected to serve as a solid basis towards a simulation-based daylight responsive building systems control demonstration in lighting and shading domain.

2 APPROACH

Description of The Case Study Model

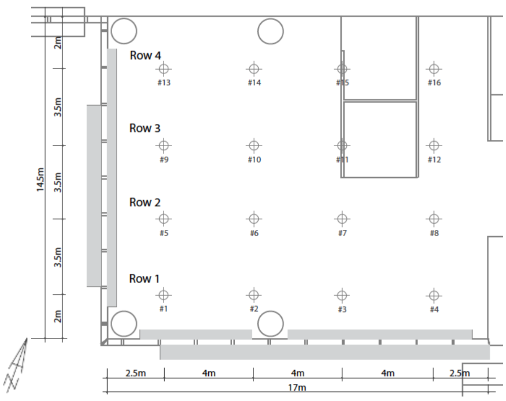
Daylight performance simulation was conducted for two offices (Area A and B) at level 11 in CREATE Tower, University Town, Singapore (see Figure 1-3). To present the performance study in a structured manner, we use the following notations: "AA" denotes Area A, and "AB" denotes Area B. AA was 14.5m by 17m, while AB was 14.5m by 18m. Both AA and AB have a floor-to-ceiling height of 2.82m and window sill height of 0.875m. The parametric plan for daylight simulation is listed in Table 1. AA and AB together with the surrounding urban context were modelled using Google SketchUp and exported to Ecotect and DAYSIM for further daylighting analysis. Also, one set (four rows) of illuminance sensor was deployed based on a grid resolution of 0.5m x 0.5m at work plane height (0.8m above the floor) to further obtain the daylight performance distributions of each office. Thus, eight rows of sensor points located parallel to the southeast facing façade were implemented (see Figure 2). Also, the electric luminaires turned off were considered.





(a) (b)

Fig. 1 (a) Site location and the surrounding urban context; (b) perspective of AA and AB in CREATE Tower



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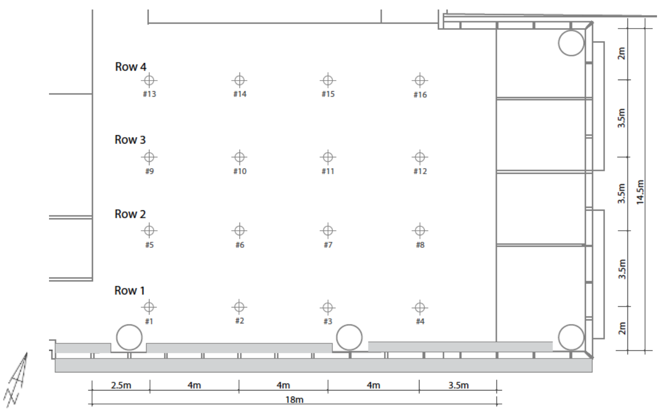

(b)

Fig. 2 Plan views and internal perspectives of AA (a) and AB (b) together with the positions of the exterior/interior shelves and sensor points.

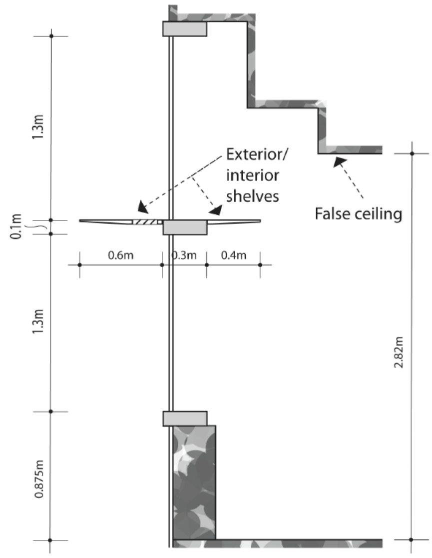

Fig. 3 An example of the façade section of AA and AB

Table 1 Parametric study for daylight simulation

Parameters	Value	Remarks
Area code	AA and AB	Base case: reflectance 80-60-40% (Ceiling-Wall-Floor), Glazing Tvis 72% (Double glazing spectrally selective), No light shelf and movable shading
Interior reflectance (Ceiling-Wall-Floor)	90-70-50% 70-50-30%	
Glazing	Tvis 62% (Double glazed Low-e) Tvis 10% (A-Si PV glazing)	
Light shelves (Reflectance: 90%)	External shelves Internal shelves External and internal shelves	
Shading	Manual shading control (active user) Manual shading control (passive user)	

Weather File

The weather file used was Singapore (latitude 1.22°N, longtitute103.59°E), with the ASHRAE International Weather for Energy Calculations (IWEC) data for Singapore, WMO 486980 downloaded from EnergyPlus weather data website [4]. The IWEC weather files for Singapore are derived from up to 18 years (1982-1999) of 8760 hourly weather data originally archived at the National Climatic Data Center. The weather data is supplemented by solar radiations and illuminance estimated on an hourly basis from earth-sun geometry and hourly weather elements (e.g. cloud coverage) [5].

Computational Simulation Tools

This study was entirely carried out by simulation using the Autodesk Ecotect Analysis [6], and DAYSIM [7,8]. DAYSIM is a RADIANCE-based day-lighting analysis tool developed by the National Research Council of Canada and the Fraunhofer Institute for Solar Energy Systems in Germany. DAYSIM employs the daylight coefficient method [9] to efficiently calculate illuminance distributions under all sky conditions in a year and the Perez sky model [10]. The simulations were performed assuming that these two selected offices (i.e., AA and AB) were occupied Monday through Friday from 9:00 to 17:00. The occupant leaves the office three times during the day (30 minutes in the morning, 1 hour at midday, and 30 minutes in the afternoon). The occupant performs a task that requires a minimum illuminance level of 500 lx [11]. For all simulations, ambient parameters in Radiance are set as shown in Table 2.

Table 2: Radiance ambient parameters

Parameter	Description	Value
-ab	Ambient bounces	5
-aa	Ambient accuracy	0.1
-ar	Ambient resolution	300
-ad	Ambient divisions	1000
-as	Ambient super-Samples	20

Shading control

A pre-configured simplified shading device model [12] in DAYSIM was conducted for the simulations of "shading control" category. This shading device model assumes that the test sites AA and AB are equipped with the venetian blinds to allow for occupants' manual control. It further assumes that the blinds may block all direct sunlight and transmit 25 percent of all diffuse daylight compared to the case when the blinds are retracted. In addition, we specifically considered following two user models for such shading device control, namely active and passive users:
i) Active users: Active users open the blinds in the morning, and partly close them to avoid visual discomfort. A user may manually fully close the blinds when direct sunlight above 50 Wm^{-2} hits the sixteen work plane sensors (0.8m above the floor). The shading device is manually retracted otherwise.
ii) Passive users keeps the blinds lowered throughout the year to avoid any glare issues.

3 PERFORMANCE METRICS FOR DAYLIGHTING

To conduct the daylight performance analysis for AA and AB, we propose a set of evaluative metrics, whereby dynamic (i.e. continuous daylight autonomy, daylight autonomy max) are considered (see Table 3). Such dynamic metrics are calculated based on an extended period of time with variable sky conditions on an annual basis. Thus, dynamic metrics could provide more valuable detailed information on daylight performance [3].

Table 3: Metrics conducted to assess daylighting performance in the offices in Tropics

Metric		Criteria	Description	Reference
Dynamic	Daylight autonomy (DA)	--	The percentage of the occupied period (hours) of the year that the minimum daylight requirement is exceeded through the year.	[1,3,13]
	Continuous daylight autonomy (DAcon)	>80%	Excellent daylight designs	[13,14]
		60-80%	Good daylight designs	
		40-60%	Adequate daylight designs	
	Daylight autonomy max (DAmax)	>5%	Not acceptable. A high probability that this will lead to a situation with a direct sunlight patch and hence glare.	[14]
		<5%	Acceptable	

Daylight Autonomy (DA) and Continuous daylight autonomy (DA_{con})

Daylight autonomy (DA) is the simplest and most widely conducted annual metric. It is generally defined as the percentage of the occupied period (hours) of the year that the minimum daylight requirement is exceeded through the year. Such metric as DA could be employed to evaluate performance at individual points and address the spatial daylight distribution [1,3]. The main advantage of daylight autonomy over the daylight factor is that it takes facade orientation and user occupancy profiles into account and considers all possible sky conditions throughout the year [13].
In addition to daylight autonomy, a modified metric "continuous daylight autonomy" (DAcon) proposed by Rogers attributes partial credit to time steps when daylight illuminance lies below the minimum illuminance level [14]. For example, in the case where 500 lx is required and 300 lx of daylight is received at a given time step, a partial credit of 300 lx/500 lx=0.6 is attributed for that time step. Thus, the metric acknowledges that even a partial contribution of daylight to illuminate a space is still beneficial.

Daylight autonomy max (DA_{max})

To simultaneously consider the potential appearance of glare, Rogers [14] also proposed a second indicator called daylight autonomy maximum (DAmax). DAmax compiles the percentage of times during a year when the illuminance at a sensor is at least 10 times the recommended illuminance. For instance, for an office space with a design illuminance of 500 lx DAmax corresponds to 5000 lx [1]. In such a situation, there is a high chance that this will correspond to a situation with a direct sunlight patch at the sensor and hence glare [15].

4 PARAMETRIC ANALYSIS RESULTS

A parametric study of daylighting performance for AA and AB using a set of simulation tools (i.e. Ecotect and DAYSIM) was carried out and generated an extensive quantity of data. The data was analyzed, some of which are presented in below.

Interior surface reflectance

The first set of daylighting performance simulations was carried out for AA and AB based on three different variants of interior surface reflectance, namely 90-70-50%, 80-60-40%, and 70-50-30% (ceiling-wall-floor, see Table 1). Table 4 indicates the percentage of space exceeding DAcon (80%, 60%, and 40%) and DAmax (5%) in view of the "interior surface reflectance" category. Figure 4 shows the daylight distributions (involving DAcon and DAmax) in AA and AB based on these three reflectance variants. The results suggest that DAcon and DAmax yielded higher levels based on a reflectance increase. For instance, increasing the reflectance from 80-60-40% to 90-70-50% for AB would increase DAcon (>80%) by 6.9%, DAcon (>60%) by 7.1%, and DAmax by 4.9%. (see Table 4). Moreover, the results shown in Figure 4 reveals that, such reflectance increment has a significant effect on DAcon for the back work place (involving Row 3 and 4) and DAmax for the front space (pertaining to Row 1) for both AA and AB.

Table 4: Simulation results regarding the percentage of space exceeding DAcon (80%, 60%, and 40%) and DAmax (5%) in view of the "interior surface reflectance" category (500 lx specified as the illuminance threshold).

Parameters	DAcon			DAmax
	>80%	>60%	>40%	>5%
90-70-50% (AA)	85.1	88.2	95.5	35.1
80-60-40% (AA)*	81.3	84.4	89.6	25.7
70-50-30% (AA)	75.0	81.3	85.8	18.8
90-70-50% (AB)	87.2	95.4	96.7	20.7
80-60-40% (AB)*	80.3	88.5	96.1	15.8
70-50-30% (AB)	69.7	78.6	91.8	11.8

*Base case

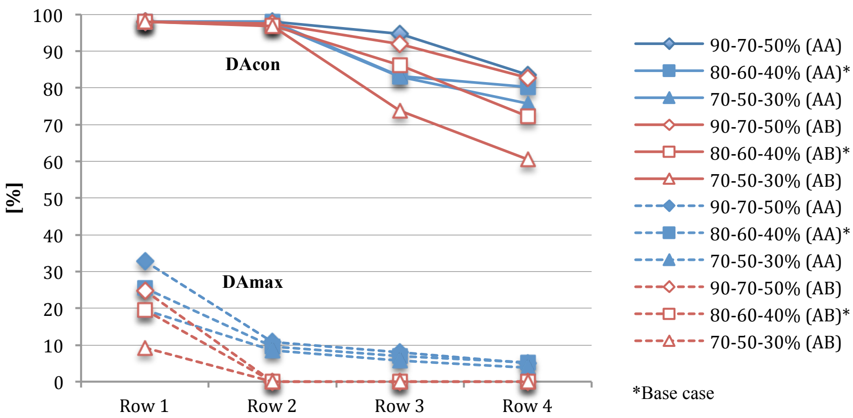

Fig. 4 Simulated results of DAcon (%, top) and DAmax (%, bottom) in view of the "interior surface reflectance" category. Each point indicates the mean values for each row (involving four sensor points) located parallel to the southeast facing window.

Glazing visual transmittance

The second set of daylighting performance simulations was performed in terms of glazing visual transmittance, whereby three different variants (Tvis 72%, Tvis 62%, and Tvis 10%) were considered. The results regarding the percentage of space exceeding DAcon (80%, 60%, and 40%) and DAmax (5%) are shown in Table 5. Figure 5 shows the daylight distributions (involving DAcon and DAmax) in AA and AB based on three glazing variants on an annual basis. Table 5 and Figure 5 highlight the large differences that occur with glazing visual transmittance. For example, in the case of AA, DAcon and DAmax indicated that the glazing with Tvis 72% has more predominant daylight appearance than the Tvis 62% glazing with DAcon(>80%) rising from 75.7% to 81.3% and DAmax(>5%) rising from 13.5% to 25.7% (see Table 5). DAcon also clearly favors 72% glazing over 62% glazing for the back work place (i.e. Row 3 and 4) (see Table 6). In addition, for the front work place of AA (specifically Row 1), 72% glazing obtained relatively higher DAmax values than 62% glazing. However, in both 62% and 72% glazing variants, the results indicated too much daylight in AA, with the occurrence of discomfort glare issues. A significant low daylight performance was observed for the variant of the PV glazing (Tvis 10%) with the DAcon (>60%) of 16.3% for AA and 11.2% for AB respectively (see Table 5). It is worthwhile to note that although the glazing visual transmittance of PV glazing is only approximately one-sixth of the 62% glazing, neither the perentage of space exceeding DAcon (>60% and >40%) nor the DAcon values are divided by six, as one would have been intuitively expected. As the results shown in Figure 5, the DAcon values with Tvis 10% for AA are in the range of 40% and 70% of 62% glazing. Similar observations have been discussed for the cases at high latitudes in past research efforts [13,15].

Table 5: Simulation results regarding the percentage of space exceeding DAcon (80%, 60%, and 40%) and DAmax (5%) in view of the "glazing" category (500 lx specified as the illuminance threshold).

Parameters	DAcon			DAmax
	>80%	>60%	>40%	>5%
Tvis72% (AA)*	81.3	84.4	89.6	25.7
Tvis62% (AA)	75.7	81.6	85.4	13.5
Tvis10% (AA)	5.6	16.3	31.6	0.0
Tvis72% (AB)*	80.3	88.5	96.1	15.8
Tvis62% (AB)	72.4	83.2	94.7	11.8
Tvis10% (AB)	4.9	11.2	23.0	0.0

*Base case

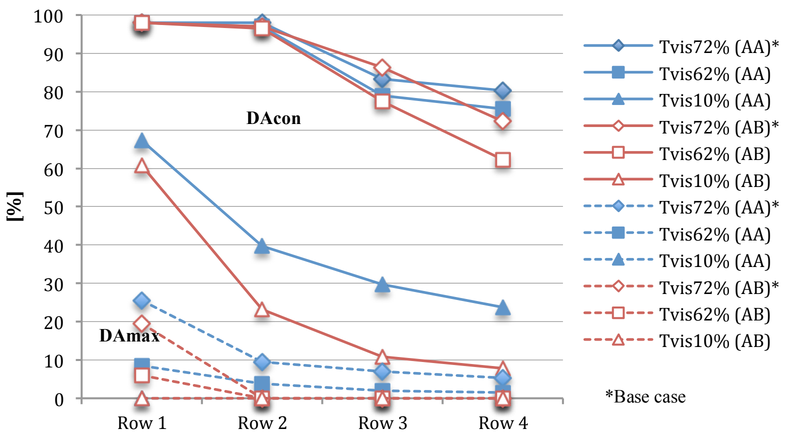

Fig. 5 Simulated results of DAcon (%, top) and DAmax (%, bottom) in view of the "glazing" category. Each point indicates the mean values for each row located (involving four sensor points) parallel to the southeast facing window.

Light shelves

The following daylighting performance simulations were performed for AA and AB in terms of light shelves. Here, we considered four design variants, namely no shelf deployed, the deployment of external shelves, internal shelves, and external + internal shelves. The simulation results (see Table 6 and Figure 6) show the influence of the light shelf deployment on the daylight performance of AA and AB according to DAcon and DAmax. The simulation results appear to suggest that the light shelves may not increase the daylight performance for AA and AB. However, they would help reduce discomfort glare. For example, as the DAcon values shown in Table 6 and Figure 6, for both AA and AB, the light shelve variants (particularly the variant with external + internal shelves) provide slightly lower performance than the base case. On the other hand, the results also imply that the application of light shelves slightly reduce DAmax. Perhaps one would expect that the light shelves reflect daylight deeper into the workspace. Furthermore, the combination of exterior and interior shelves would be expected to work best in providing a relative high uniformity of daylight throughout the workspace. However, the results represent a sobering answer to this inquiry. This difference may be attributable to the observation, that the existing ceiling design (see Figure 3) could not allow for effective daylight reflection onto the ceiling and penetrate deep into the workspace, and thus has less impact on the improvement of daylight performance.

Table 6: Simulation results regarding the percentage of space exceeding DAcon (80%, 60%, and 40%) and DAmax (5%) in view of the "lighting shelves" category (500 lx specified as the illuminance threshold).

Parameters	DAcon			DAmax
	>80%	>60%	>40%	>5%
No Shelf (AA)*	81.3	84.4	89.6	25.7
Ext. Shelves (AA)	81.2	84.3	89.2	24.3
Int. Shelves (AA)	81.2	84.3	89.2	22.9
Ext.+Int. Shelves (AA)	80.9	84.4	89.2	21.5
No Shelf (AB)*	80.3	88.5	96.1	15.8
Ext. Shelves (AB)	77.6	87.5	95.4	13.5
Int. Shelves (AB)	77.6	87.8	96.1	13.5
Ext.+Int. Shelves (AB)	75.0	84.9	94.7	11.8

*Base case

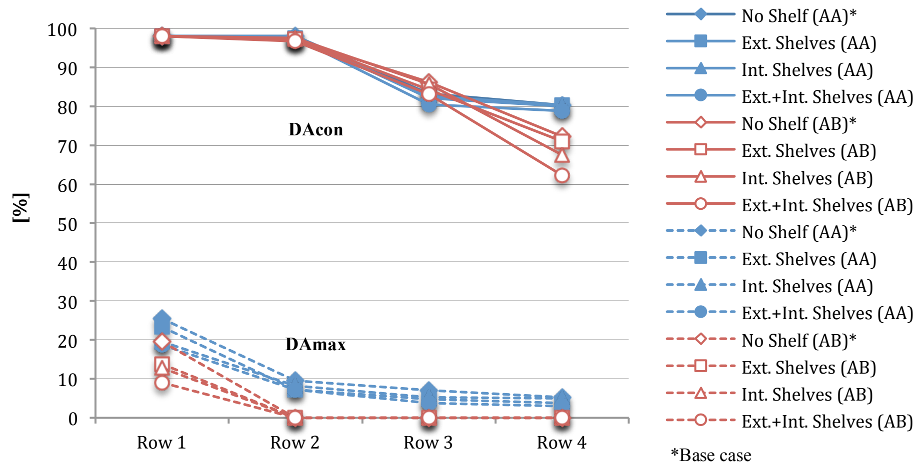

Fig. 6 Simulated results of DAcon (%, top) and DAmax (%, bottom) in view of the "light shelves" category. Each point indicates the mean values for each row (involving four sensor points) located parallel to the southeast facing window.

Shading control

In most of the buildings, the occupants could operate the shading device to achieve the desirable visual comfort and avoid higher levels of glare and overheating issues. In the last set of simulations, we investigated the impact of manual shading control behaviors on the annual amount of daylight within AA and AB (see Table 7 and Figure 7). Thereby, as described in section 2, we specifically considered two user models (i.e. active and passive users) and one simpler blind model (pertaining to the manual control of the venetian blinds). The results reveals that the shading control behaviors lead to a significant reduction in DAmax. For instance, in AB, DAmax falls from 15.8% to 11.8% and 0% for the active and passive shading control behaviors respectively, suggesting that they are less prone to glare. However, DAcon raises a warning flag for the application of passive shading control behaviors, which clearly lead to the poor daylight appearance in both AA and AB. This implies that the occupants keep the blinds lowered throughout the year to avoid the glare issues and are expected to perform their tasks with the condition of poor daylight performance and/or supplementary electric lighting. Here, we see a challenge. We conclude that modern façade design in office buildings that offer high window-to-wall ratio for increasing the daylight level, must also pay attention to the glare control strategies so that the efficiency of electric lighting as well as the visual comfort could be effectively achieved.

Table 7: Simulation results regarding the percentage of space exceeding DAcon (80%, 60%, and 40%) and DAmax (5%) in view of the "shading control" category (500 lx specified as the illuminance threshold).

Parameters	DAcon			DAmax
	>80%	>60%	>40%	>5%
No movable shades (AA)*	81.3	84.4	89.6	25.7
Shades control-active user (AA)	77.8	84.0	87.5	19.8
Shades control-passive user (AA)	41.0	51.4	67.7	0.0
No movable shades (AB)*	80.3	88.5	96.1	15.8
Shades control-active user (AB)	73.4	84.5	95.1	11.8
Shades control-passive user (AB)	26.3	42.1	55.9	0.0

*Base case

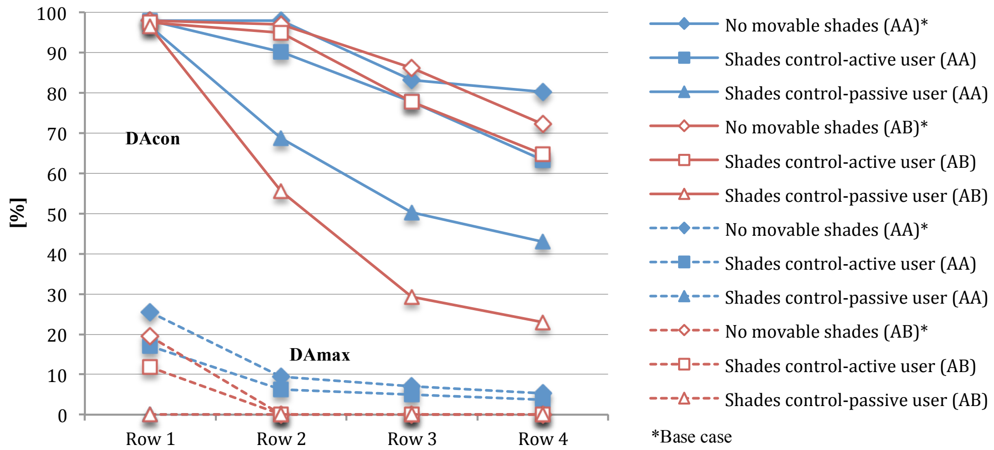

Fig. 7 Simulated results of DAcon (%, top) and DAmax (%, bottom) in view of the "shading control" category. Each point indicates the mean values for each row (involving four sensor points) located parallel to the southeast facing window.

5 CONCLUSION

For the optimal visual performance of each office space, one key point is how the occupants use the space (involving user requirements) and how we introduce daylight in an effective and appropriate manner. Such office spaces that are continually occupied for long-term periods of time and where daylighting would increase the productivity and even the energy efficiency of the space should be a high daylighting priority. Also, the provision of visual comfort (pertaining to low glare and good uniformity of daylight level) is critical. Specifically, the modernist glass curtain wall, which admits and traps not only daylight but solar heat, has been commonly adopted for the office building design in Singapore. The development of architecture design and building systems appropriate to Singapore's tropical climate as well as high-density urban context becomes an urgent issue.

This research effort contributed to above-mentioned topics. In this paper, we have obtained the results that have illustrated a parametric approach toward formulating, analyzing, and simulating day-lighting performance for a high-rise building in Singapore. Based on the author's knowledge, this research effort represents the first systematic approach for dynamic daylight simulations in standard, existing open plan offices in the Tropics, whereby four passive design categories (i.e. interior surface reflectance, glazing visual transmittance, light shelves, and shading control) were considered. We demonstrated the process and the generation of a set of computational performance simulation models on the basis of documentation of the building (geometry, construction, systems, operation), occupancy, and external (weather) conditions. The results indicate that certain passive design strategies such as interior surface reflectance, glazing visual transmittance, and shading control have significant effects on DAcon and DAmax. There are other strategies (involving light shelves), however, that have rather lower effects on these two metrics. Ongoing work involves long-term data collection regarding indoor illuminance, discomfort glare, temperature, electric lighting energy usage, occupancy patterns, and sky illuminance. Subsequently, a detailed and dynamic digital visual performance model will be generated and calibrated based on collected data. The calibrated models will be then applied to compare and evaluate retrofit and enhancement alternatives in view of building integrity, visual, and energy performance. Furthermore, the outcomes of this effort are expected to serve as a solid basis towards a simulation-based daylight responsive building systems control in lighting and shading domain.

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