SIMULATION-ASSISTED DAYLIGHT PERFORMANCE ANALYSIS IN A HIGH-RISE OFFICE BUILDING IN SINGAPORE

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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 metrics for tropical office buildings. We first evaluated an array of daylight performance metrics, namely daylight factor, daylight autonomy, continuous daylight autonomy, daylight autonomy max, and useful daylight illuminance. Subsequently, a systematic approach toward assessing daylight performance is presented. The approach is exemplified using the case study of two selected offices in the CREATE Tower, an air-conditioned office building located in Singapore. These study sites were investigated based on the above-mentioned metrics. The results indicate that both sites offer predominantly daylight appearances that can provide sufficient ambient lighting for the majority of the year. However, inner cores of both sites would have to rely on supplementary electric lighting to achieve desirable indoor visual comfort. On the other hand, strong potentials of glare and discomfort issues may occur in the perimeter zones of these offices together with overheating effects. Passive/active strategies may be conducted to significantly block and/or redirect the direct sunlight and thus effectively increase the useful daylight levels for the occupants. 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, dynamic metrics, performance simulation, 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 (Reinhart et al. 2006; Cantin and Dubois 2011; DiLaura 2011). In this context, the research effort describes a systematic approach toward obtaining and assessing simulation-based daylight performance data from high-rise office buildings.

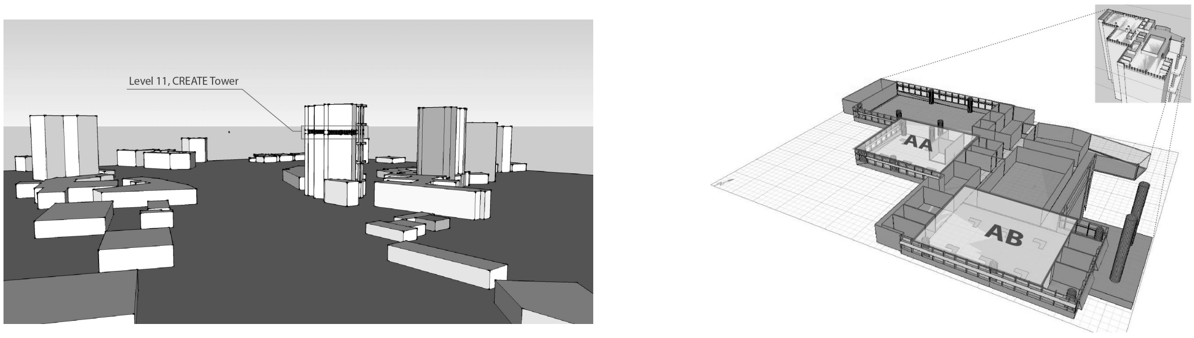
This approach is currently being applied within the framework of a living lab project, with the support of the Singapore-Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST) Program. Thereby, amongst other activities, local climate and building performance (involving visual/ thermal 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 five daylight performance metrics for tropical office buildings. We first evaluated an array of current daylight performance metrics. Thereby, both static (daylight factor) and dynamic (daylight autonomy, continuous daylight autonomy, daylight autonomy max, useful daylight illuminance) daylight performance metrics are considered. Subsequently, a systematic approach toward assessing daylight performance based on above-mentioned metrics is presented. The approach is exemplified using two selected offices (Area A and B) in CREATE Tower, an existing air-conditioned office building located in Singapore. 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 tropics. Furthermore, the outcomes of this effort are expected to serve as a solid basis towards a simulation-based daylight-responsive building systems control and demonstration in lighting and shading domain.

2. APPROACH

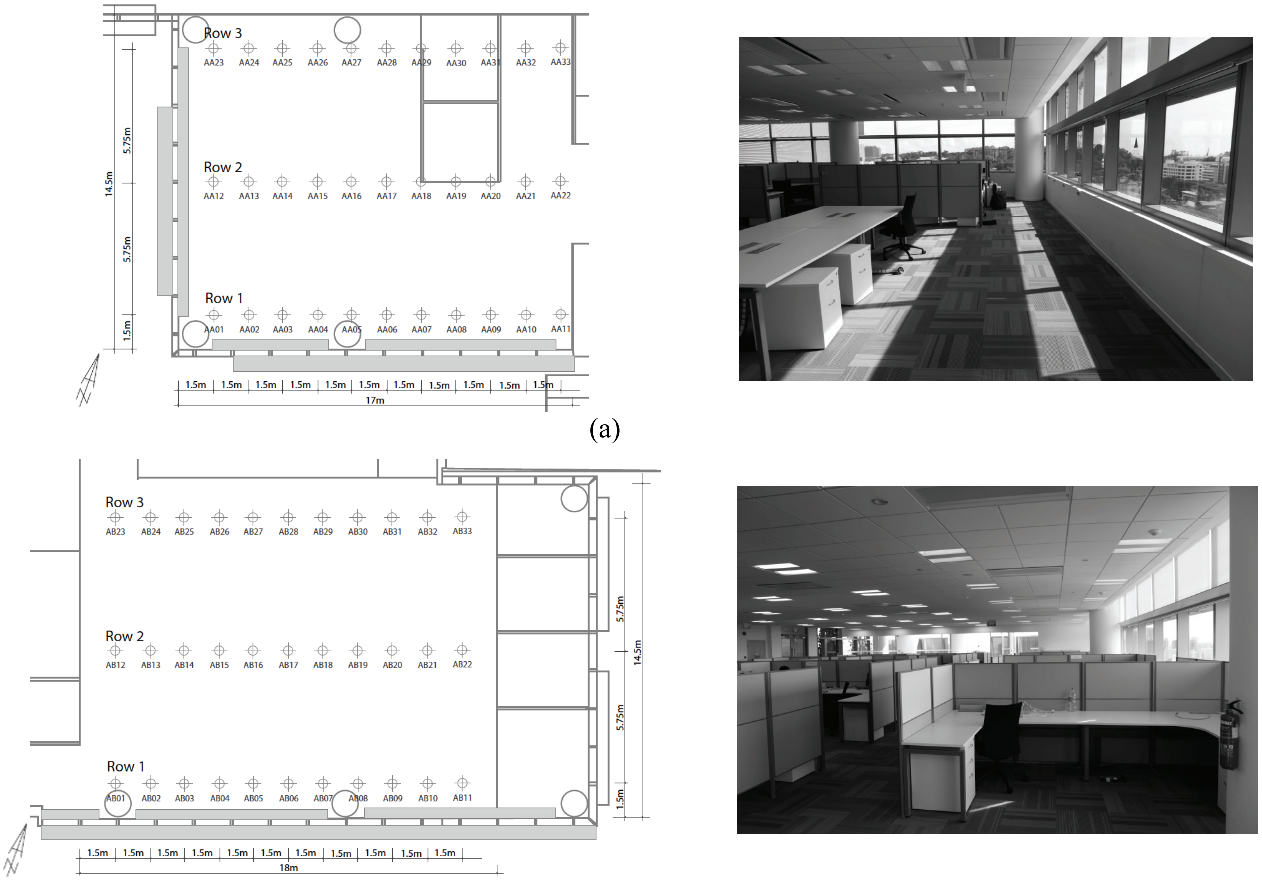
2.1 Description of the case study model

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. The information regarding office geometry, building materials, and optical properties of the surfaces for daylight simulation are 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 (three 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, six rows of illuminance sensor points (i.e. AA01-11, AA12-22, AA23-33, AB01-11, AB12-22, AB23-33) were considered in relation to the distance from south-west perimeter (see Figure 2). Thereby, the electric luminaires turned off were considered. However, as the base case study, no shading devices were assumed at current stage. The requirements (involving properties) and effects of the shading devices and interior furniture will be studied in the future stage.



(a) (b)

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



(a)

(b)

Figure 2: Plan views and internal perspectives of AA (a) and AB (b) together with the positions of the exterior/interior shelves and sensor points (i.e. AA01-AA33, AB01-AB33).

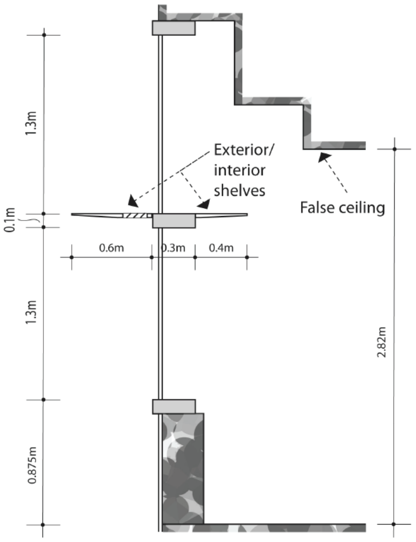


Figure 3: Façade section of AA and AB

Table 1: Building materials and optical properties.

Area Code	**AA**	**AB**
Width (m)	17	18
Depth (m)	14.5	14.5
Height (m)	2.82 for both areas	
Window sill height (m)	0.875 for all windows	
Glazing Tvis	0.61 for all windows	
Exterior & interior shelves (m)	0.6 & 0.4 for both areas	
Reflectance of shelf surface	0.8 for both areas	
Reflectance of ceiling surface	0.7 for both areas	
Reflectance of wall surface	0.6 for both areas	
Reflectance of floor surface	0.4 for both areas	
Reflectance of ground	0.2	

2.2 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 (DOE 2013a). 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) (DOE 2013b).

2.3 Computational Simulation Tools

This study was entirely carried out by simulation using the Autodesk Ecotect Analysis (Autodesk 2013), and DAYSIM (Reinhart and Breton 2009; Reinhart et al. 2013). 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 (Trezenga and Loe 1998) to efficiently calculate illuminance distributions under all sky conditions in a year and the Perez sky model (Perez et al. 1993). 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 (SS 2013). 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

2.4 Performance Metrics For Daylighting

To conduct the daylight performance analysis for AA and AB, we propose a set of evaluative metrics, whereby both static (daylight factor) and dynamic (daylight autonomy, continuous daylight autonomy, daylight autonomy max, and useful daylight illuminance) are considered (see Table 3). Daylight factor for static simulation is calculated at single point in time, while 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 (DiLaura 2011).

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

Metric		Criteria	Description	Reference
Static	Daylight factor (DF)	<2%	Gloomy appearance with rare daylight. Electric lighting needed during daylight hours.	(Trezenga and Loe 1998; Pollock et al. 2009; Cantin and Dubois 2011)
		2%-5%	Predominant daylight appearance. Some supplementary electric lighting required.	
		>5%	Daytime electric lighting rarely needed. Thermal/glare issues may occur along with the high levels of daylight.	
Dynamic	Daylight autonomy (DA)	--	The percentage of the occupied period (hours) of the year that the minimum daylight requirement is exceeded through the year.	(Reinhart 2002; Reinhart et al. 2006; DiLaura 2011)
	Continuous daylight autonomy (DAcon)	>80%	Excellent daylight designs	(Reinhart 2002; Rogers 2006)
		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.	(Rogers 2006)
		<5%	Acceptable	
	Useful daylight illuminance (UDI)	<100 lx	Gloomy room with insufficient daylight.	(Nabil and Mardaljevic 2005a; Nabil and Mardaljevic 2005b)
		100-2000 lx	The room is with useful daylight levels for the occupants	
		>2000 lx	The room is too bright and exceeds the upper threshold of the useful range. Higher levels glare or discomfort maybe delivered together with overheating issues.	

2.4.1 Daylight Factor (DF)

Daylight factor (DF) is the most widely conducted metric for daylight performance in buildings (DiLaura 2011). A daylight factor is the ratio of internal light level at one point in a building to the unshaded external light level under the Standard CIE overcast Sky (Trezenga and Loe 1998; Pollock 2009; Cantin and Dubois 2011). Daylight factor is static simulation (i.e. at one time step) and used in architecture and building design for assessing the internal daylight availability as perceived on the working plane or surface based on the occupants' work activities.

2.4.2 Daylight Autonomy (DA)

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 (Reinhart 2006; DiLaura 2011). 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 (Reinhart 2002).

2.4.3 Continuous daylight autonomy (DA_{con})

In addition to daylight autonomy, a modified metric "continuous daylight autonomy" (DA_{con}) proposed by Rogers attributes partial credit to time steps when daylight illuminance lies below the minimum illuminance level (Rogers 2006). 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.

2.4.4 Daylight autonomy max (DAmax)

To simultaneously consider the potential appearance of glare, Rogers (2006) also proposed a second indicator called daylight autonomy maximum (DA_{max}). DA_{max} 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 DA_{max} corresponds to 5000 lx (Reinhart 2006). 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 (Dubois and Flodberg 2013).

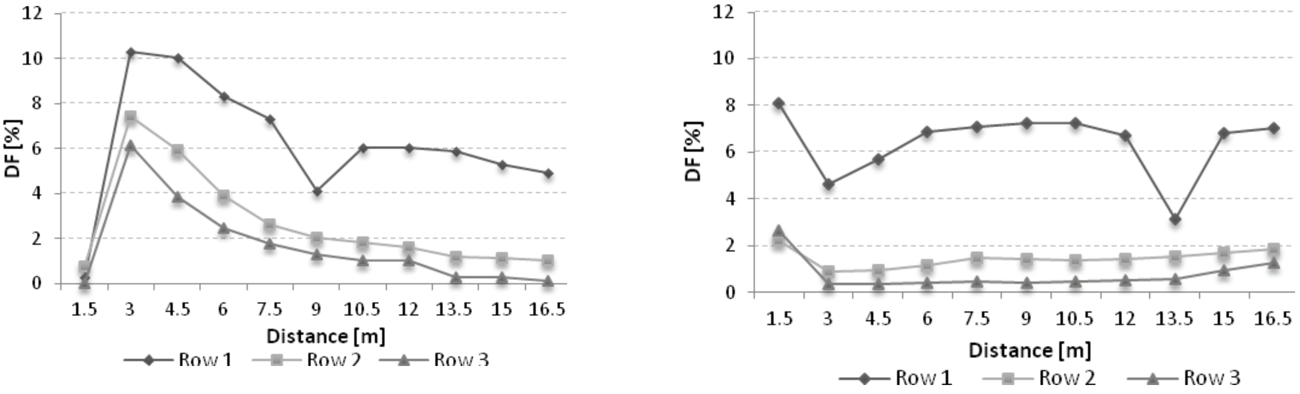
2.4.5 Useful daylight illuminance (UDI)

Useful Daylight Illuminance (UDI) is another modified version of Daylight Autonomy (Nabil and Mardaljevic 2005a; Nabil and Mardaljevic 2005b). This metric complies the number of operating hours based upon three illuminance ranges, namely 0-100 lx, 100-2000 lx, and greater than 2000 lx. Useful daylight is considered to occur when the daylight illuminance fall into the range of 100 lx and 2000 lx ($UDI_{100-2000}$) (DiLaura 2011). Thus, it provides full credit only to values between 100 lx and 2,000 lx suggesting that horizontal illumination values outside of this range are not useful.

3. RESULTS

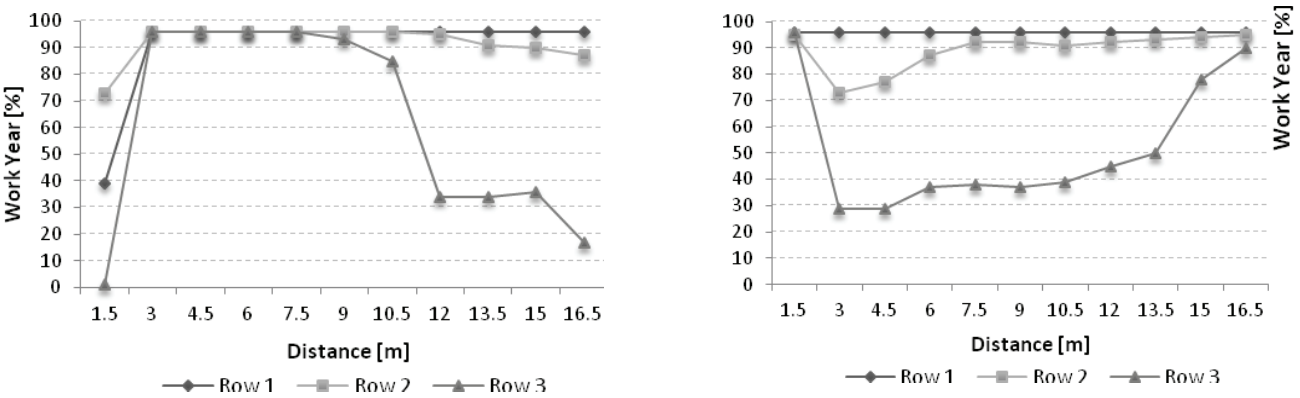
A study of daylighting performance for AA and AB using a set of simulation tools (i.e. Ecotect and DAYSIM) was carried out and generated an extensive quantity of data. The data was analyzed, some of which are presented in below.

Figure 4 shows the daylight factor (DF) measured for AA and AB. To provide a series of dynamic daylight performance analysis for AA and AB, such metrics as DA_{con} (see Figure 5), DA_{max} (see Figure 6), and UDI (see Figure 7-9) were conducted respectively. Figure 5 depicts, for AA and AB, the DA_{con} with 500 lx specified as the DA threshold ($DA_{con}500$) and the DA_{con} values on an annual basis. Figure 6 shows the percentage of times during a year when the illuminances at the sensor points exceeded 10 times the illuminance threshold (500 lx). In an effort to compare the UDI metrics in AA and AB based on the UDI criteria (illuminance range: between 100 lx and 2000 lx, greater than 2000 lx, and less than100lx) were presented in Figure 7-9 respectively.



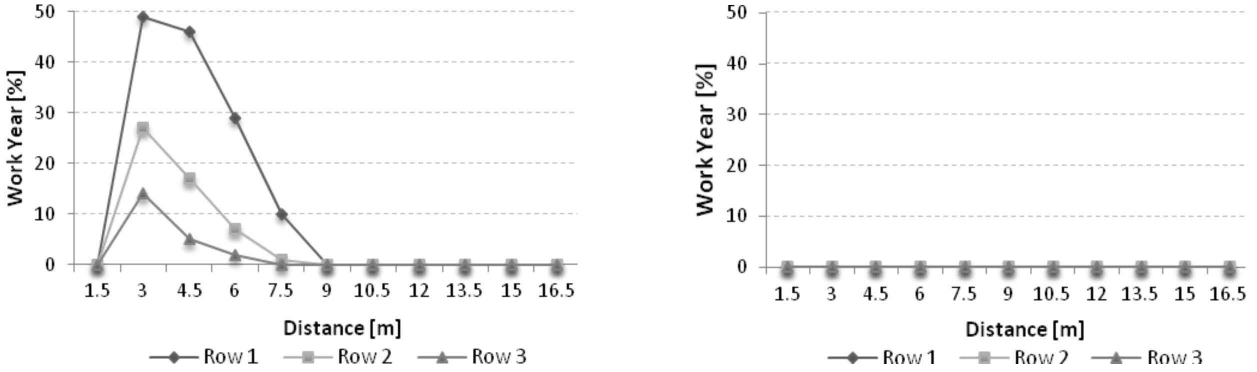
(a) for AA
(b) for AB

Figure 4: Simulated Daylight Factor (DF, %)



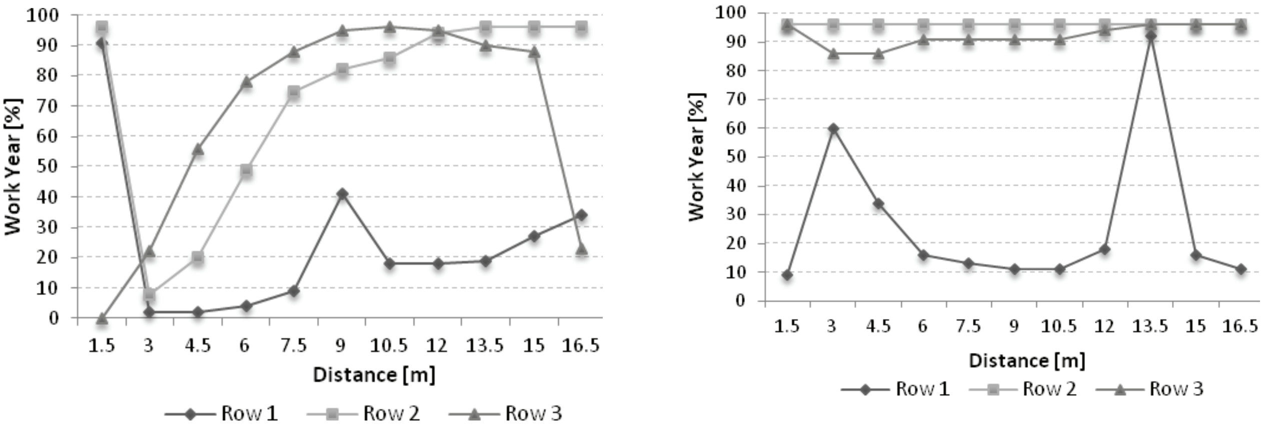
(a) for AA
(b) for AB

Figure 5: Simulated DAcon (%, 500 lx)



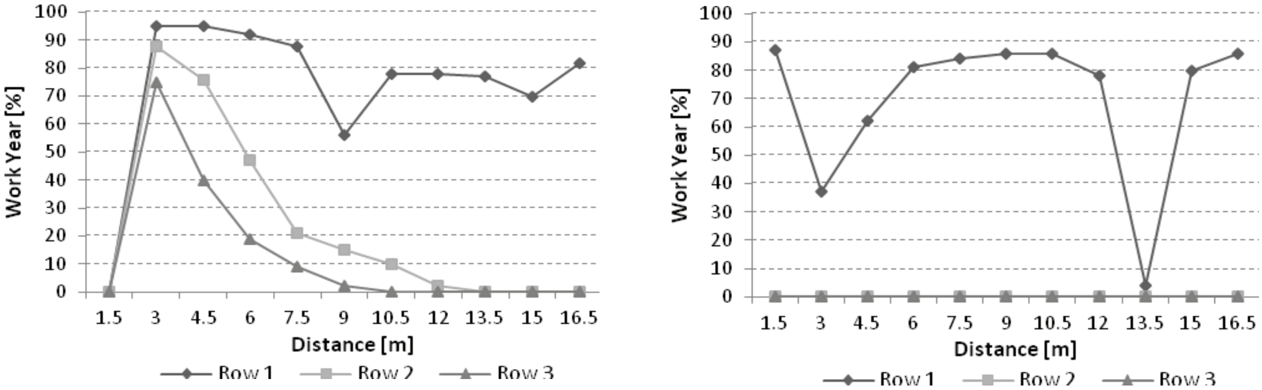
(a) for AA
(b) for AB

Figure 6: Simulated DAmax (%)



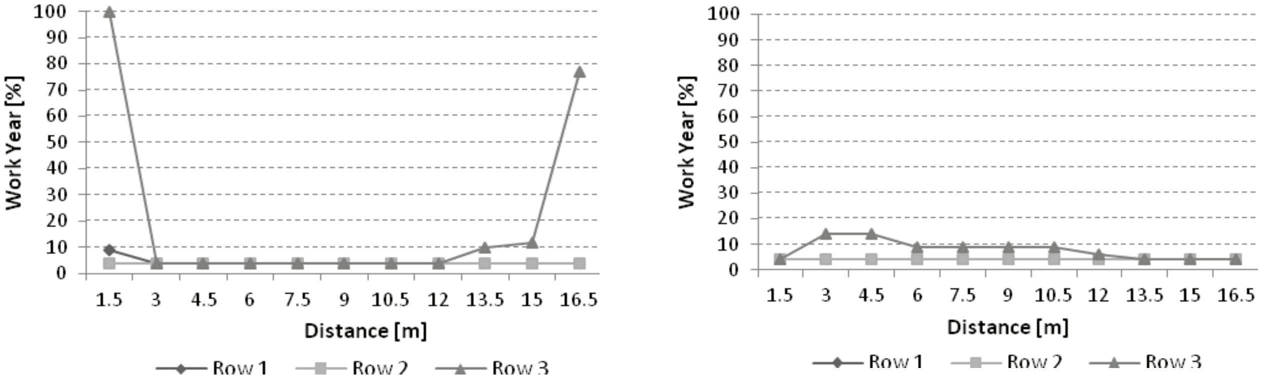
(a) for AA (b) for AB

Figure 7: Simulated UDI (%, 100-2000 lx)



(a) for AA (b) for AB

Figure 8: Simulated UDI (%, >2000 lx)



(a) for AA (b) for AB

Figure 9: Simulated UDI (%, <100 lx)

4. DISCUSSION

For the 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. In addition, as described in section 2.4, both static and dynamic daylight metrics were applied in this study. The simulation results support a number of initial conclusions, as discussed in the following two sections, namely daylight quantity and quality.

4.1 Daylight Quantity

DAcon (>60%) reveals that more than two thirds of the sensor points in both AA and AB obtaining continuous daylight autonomies over 60 percent. It implies that AA and AB offer predominantly daylight appearances that can provide sufficient ambient lighting for the majority of the year (see Figure 5). Moreover, as the result shown in Figure 5, AA receives relative high uniformity of daylight throughout the space with four fifths of the sensor points obtaining DAcon (>80%). This difference may be attributable to the building layout design, that more daylight may deeper penetrate into AA (from the fenestrated southwest and southeast oriented facades) than into AB (from the fenestrated southeast oriented facades). However, it is worthwhile to note that partial sensor points (particularly in Row Three) of AA and AB obtain continuous daylight autonomies under 40 percent on an annual basis. This means that the occupants are expected to perform their tasks with the condition of poor daylight performance in the inner core of AA and AB. Electric lighting retrofit design must thus pay particular attention to supplementing appropriate electric lighting while offering zoning consideration in manipulation options.

4.2 Daylight Quality

The results clearly show that the perimeter zones of AA and AB receive excessive direct and indirect sunlight (see Figure 4, 6, 7 and 8). Specifically, UDI (100-2000 lx) and UDI (>2000 lx) raise a warning flag for AA, which has a significantly brighter daylight appearance and less useful daylight level than AB. On the other hand, for AB, there are sensor points (mainly in Row 1), which, while limited in number, are overlit. Moreover, DAmax reveals that for AA nearly a quarter of sensor points (located in perimeter zones) is subject to more than 5000 lx over 5% on an annual basis. This implies that, strong potentials of glare and discomfort issues may occur in such perimeter zones together with overheating effects. As alternatives to desirable indoor visual comfort that require the elimination of the glare issues, passive/active elements (pertaining to shelves, louvers, and blinds) would significantly block and/or redirect the direct sunlight and thus effectively increase the useful daylight levels for the occupants. Thereby, supplementary electric lighting control should be considered to accommodate the dynamic visual performance complexity.

5. CONCLUSION AND FUTURE WORK

We have obtained preliminary results which have illustrated a systematic approach toward formulating, analyzing, and simulating day-lighting performance for a high-rise building in Singapore. 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. 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.

ACKNOWLEDGMENTS

This research is funded by the Republic of Singapore's National Research Foundation through a grant to the Berkeley Education Alliance for Research in Singapore (BEARS) for the Singapore-Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST) Program. BEARS has been established by the University of California, Berkeley as a center for intellectual excellence in research and education in Singapore.

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