PERFORMANCE-BASED ASSESSMENT OF DAYLIGHT ON TROPICAL BUILDINGS- A CASE STUDY

CHIEN Szu-cheng[1,2] and Tseng King Jet[3]
[1] Berkeley Education Alliance for Research in Singapore (BEARS) center, Singapore
[2] Energy Research Institute @ Nanyang Technological University, Singapore
[3] School of Electrical & Electronic Engineering, Nanyang Technological University, Singapore

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 CREATE Tower, an air-conditioned office building located in Singapore. Thereby, a set of variants was generated based on four investigated configurations 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.

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 comfort, 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.

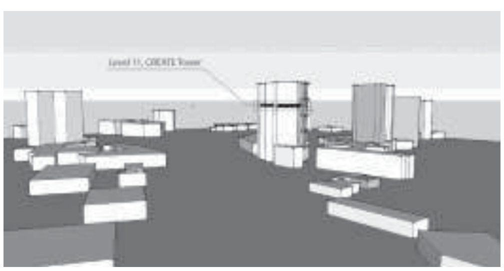
Proceedings of the SB 13 Singapore — Realising Sustainability in the Tropics

ISBN: 978-981-07-7377-9

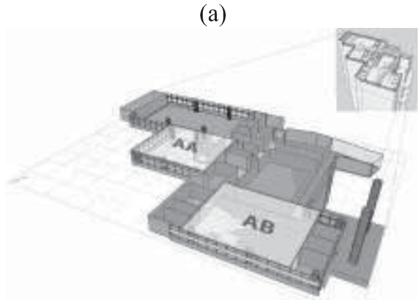
APPROACH

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 1and 2). To present the performance study in a structured manner, we use the following notations: "AA" denotes Area A, and "AB" denotes Area B. High ceiling is specified with code "H", whereas low ceiling is specified with code "L". In addition, we refer to the unshaded windows henceforth as "1" and the shaded windows (adorned with exterior/interior shelves) as "2" respectively. For each area, four different configurations were then evaluated (i.e., H1, H2, L1, L2, as per Figure 3). Thus, eight variants (AAH1, AAH2, AAL1, AAL2, ABH1, ABH2, ABL1, ABL2) were considered. The information regarding office geometry, building materials, and optical properties of the surfaces for daylight simulation are listed in Table 1. The whole variants together with the surrounding urban context were modelled using Google SketchUp and exported to Ecotect and DAYSIM for further daylighting analysis. Also, a set of illuminance sensor points was deployed in AA and AB based on a grid resolution of 1m x 1m at work plane height (0.8m above the floor). 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.

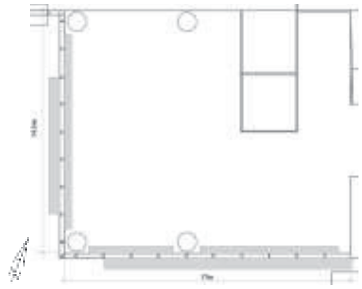


(a)

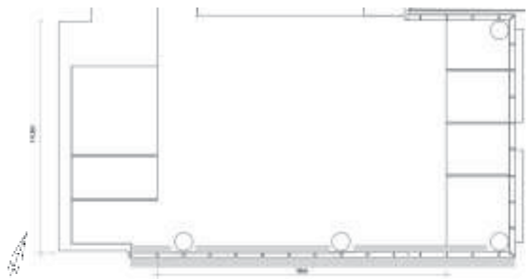


(b)

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



(a)



(b)

Figure 2 Plan views of AA (a) and AB (b) together with the positions of the exterior and interior shelves.

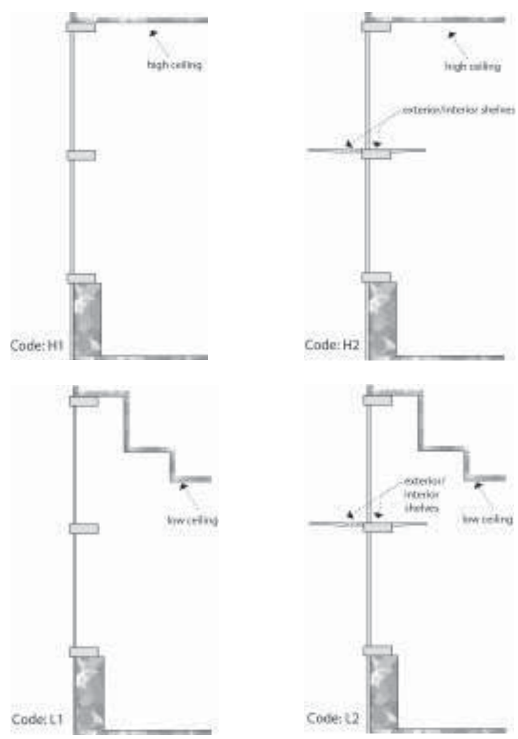


Figure 3 Illustration of four investigated configurations, namely H1, H2, L1, L2

Table 1 Building materials and optical properties

Area Code	**AA**	**AB**
Width (m)	17	18
Depth (m)	14.5	14.5
Height (m)	3.72 (high ceiling)/ 2.82 (low ceiling) 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	

Weather File

The weather file used was Singapore (latitude 1.22°N, longtitute 103.59°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 Centre. 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).

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

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).

i) 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.

ii) 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).

iii) Continuous daylight autonomy (DAcon): 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 (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.

iv) Daylight autonomy max (DAmax): To simultaneously consider the potential appearance of glare, Rogers (2006) 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 (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).

v) 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 (UDI100-2000) (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.

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.

Table 4 shows the simulation results of eight specified variants (i.e., AAH1, AAH2, AAL1, AAL2, ABH1, ABH2, ABL1, ABL2) in accordance with the previously described daylight performance metrics, namely daylight factor (DF), daylight autonomy (DA), Continuous daylight autonomy (DA_{con}), Daylight autonomy max (DA_{max}), and Useful daylight illuminance (UDI). Note that the simulation results were calculated based on the mean values. To provide a series of dynamic daylight performance analysis for these eight variants, such metrics as DA_{con} (see Figure 4), DA_{max} (see Figure 5), and UDI (see Figure 6) were conducted respectively. Figure 4 depicts the DA_{con} with 500 lx specified as the DA threshold (DA_{con}500) and the percentage of the space exceeded 500 lx over 40%, 60%, and 80% of the time on an annual basis. Figure 5 shows the percentage of the space exceeded 10 times the illuminance threshold (500 lx) over 5% of the time on an annual basis. In an effort to compare the UDI metric in these eight variants based on the UDI criteria (illuminance range: less than100 lx, in the range of 100 and 2000 lx, and greater than 2000 lx) is presented in Figure 6.

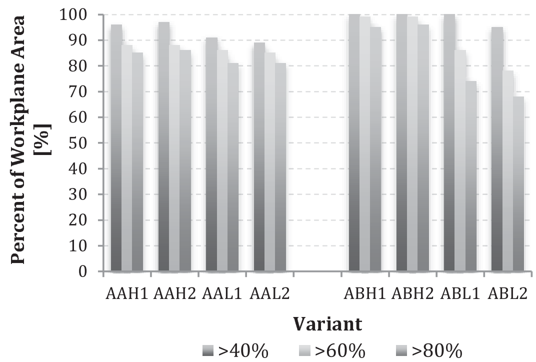


Figure 4 The percentage of workplane area above 40%, 60%, and 80% DAcon (500 lx)

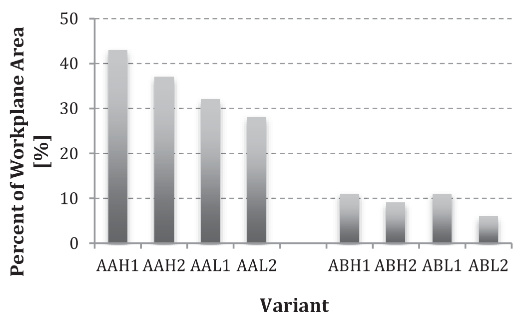


Figure 5 Percentage of workplane area above 5% DAmax

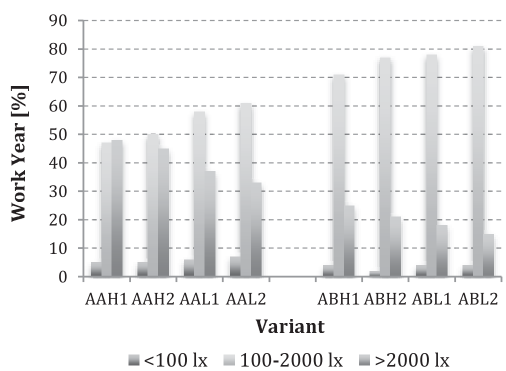


Figure 6 UDI (mean values, %) for eight variants, based on three illuminance range: less than100 lx, 100 lx to 2000 lx, and greater than 2000 lx

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. The simulation results support a number of initial conclusions, as discussed in the following two sections, namely daylight quantity and quality.

Daylight Quantity

The simulation results show that whole variants offer predominantly daylight appearances that can provide sufficient ambient lighting for the majority of the year (see Table 4 and Figure 4). According to the DF metric, these eight variants meet the DF (2%-5%) criteria. Moreover, DA_{con} (>60%) reveals that these eight variants deliver high uniformity of daylight throughout the spaces with greater than 80% of the space obtaining continuous daylight autonomies over 60 percent. On the other hand, as DAcon (>60% and >80%) shown in Figure 4 imply, there are variants (particularly ABL1 and ABL2) with passive design elements (i.e. low ceiling and exterior/interior shelves), which, while increase in items, give relatively lower levels of daylight appearance.

Daylight Quality

The results clearly show that higher percentage of workplane area in AA receives direct sunlight than in AB (see Table 4, Figure 5, Figure 6). This difference may be attributable to the building layout design, that more direct sunlight may deeper penetrate into AA (from the fenestrated southwest and southeast oriented facades) than into AB (from the fenestrated southeast oriented facades). Thus, the variants in AA are with less useful daylight level and more prone to glare. Specifically, UDI (>2000 lx) of 48% and DAmax of 43% raise a warning flag for Variant AAH1, which has a significantly brighter daylight appearance than the other seven variants. This implies that, strong potentials of glare and discomfort issues may occur in such space together with overheating effects. On the other hand, the results (see Figure 5 and 6) appear to suggest that the passive design elements (pertaining to low ceiling height and exterior/interior shelves) may significantly block and/or redirect the direct sunlight and thus effectively increase the useful daylight levels for the occupants (particularly in AA). The results also demonstrate that the effect of exterior/interior shelves is significant and as important as the effect of low ceiling height. For example, according to the DAmax metric, AAL2 is superior to the three other AA variants followed by AAL1, AAH2, and AAH1 (see Figure 5). Also, UDI (100-2000 lx) and UDI (>2000 lx) indicate that AAL2 is superior to the worst Variant AAH1 with UDI (100-2000 lx) rising from 47% to 61% and UDI (>2000 lx) decreasing from 48% to 33% (see Table 4 and Figure 6). Conversely, the results express that, in terms of the variants of AB, low ceiling and exterior/interior shelves have relatively low impacts on the probability reduction for discomfort glare (see Table 4 and Figure 6).

CONCLUSION

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. Further developments of this study are expected to facilitate a detailed and dynamic daylight performance model, whereby the manual/automated blinds, interior office furniture, and lighting energy usage data are considered. The calibrated models will be then applied to compare and evaluate retrofit and enhancement alternatives (involving building envelope components) 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.

ACKNOWLEDGMENT

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.

REFERENCES

1. Reinhart, C. F., Mardaljevic, J., and Rogers, Z., 2006. Dynamic Daylight Performance Metrics for Sustainable Building Design. *Leukos* 3(1):p. 7-31.
2. Cantin, F. and Dubois, M., 2011. Daylighting metrics based on illuminance, distribution, glare and directivity. *Lighting Research and Technology* 43:p. 291-307.
3. DiLaura, D. L., 2011. *The lighting handbook: reference and application*. New York, NY:

Illuminating Engineering Society of North America.

4. The EnergyPlus Website, [online], Available: http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm/region=5_southwest_pacific_wmo_region_5/country=SGP/cname=Singapore [1 May 2013]
5. The EnergyPlus Website, [online], Available: http://apps1.eere.energy.gov/buildings/tools_directory/software.cfm/ID=369/pagename=alpha_list [1 May 2013]
6. The Ecotect Website, [online], Available: http://usa.autodesk.com/ecotect-analysis/ [30 April 2013]
7. Reinhart, C.F., and Breton, P.F., 2009. Experimental Validation of Autodesk® 3ds Max® Design 2009 and DAYSIM 3.0. *Leukos* 6(1):p. 7-35.
8. Reinhart, C.F., Lagios, K., Niemasz, J., Jakubiec, A. DIVA for Rhino Version 2.0. [online]. Available: http://www.diva-for-rhino.com/ [15 April 2013]
9. Trezenga, P., and Loe, D., 1998. *The Design of Lighting*. London: E & FN Spon.
10. Perez, R., Seals, R., and Michalsky, J. 1993. All-weather model for sky luminance distribution preliminary configuration and validation. *Solar Energy.* 50: p. 235–245.
11. SS 531 - 1, Code of practice for lighting of work places, [online], Available: http://www.singaporestandardseshop.sg/data/ECopyFileStore/070918100959Preview%20-%20SS%20531-1-2006.pdf [1 April 2013]
12. Pollock, M., Roderick, Y., McEwan, D., and Wheatley, C. 2009. Building simulation as an assisting tool in designing an energy efficient building: A case study. *White Paper*. Glasgow: Integrated Environmental Solutions Limited.
13. Reinhart, C.F. 2002. Effects of interior design on the daylight availability in open plan offices. *Report NRCC-45374*. Ottawa: National Research Council of Canada, Institute for Research in Construction.
14. Rogers, Z. 2006. *Daylight metric development using daylight autonomy calculations in the sensor placement optimization tool*. Boulder, CO: Architectural Energy Corporation.
15. Dubois, M-C., and Flodberg, K. 2013. Daylight utilisation in perimeter office rooms at high latitudes: Investigation by computer simulations. *Lighting Research and Technology,* 45 (1): p. 52-75.
16. Nabil, A., and Mardaljevic, J. 2005a. Useful Daylight Illuminance: A New Paradigm to Access Daylight in Buildings. *Lighting Research & Technology*, 37(1):p. 41-59.
17. Nabil, A., and Mardaljevic, J. 2005b. Useful daylight illuminances: A replacement for daylight factors. *Energy and Buildings*, 38(7): p. 905-913.

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

Metric	Criteria	Description	Reference
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.	
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.	

Table 4 Simulation results of eight variants

Code	AAH1	AAH2	AAL1	AAL2	ABH1	ABH2	ABL1	ABL2
Daylight Factor (DF)	5%	4%	4%	3%	4%	3%	3%	3%
Daylight Autonomy (DA)	81%	81%	75%	73%	84%	82%	64%	57%
Continuous daylight autonomy (DAcon) >40%	96%	97%	91%	89%	100%	100%	100%	95%
>60%	88%	88%	86%	85%	99%	99%	86%	78%
>80%	85%	86%	81%	81%	95%	96%	74%	68%
Daylight autonomy max (DAmax) >5%	43%	37%	32%	28%	11%	9%	11%	6%
Useful daylight illuminance (UDI) <100 lx	5%	5%	6%	7%	4%	2%	4%	4%
100-2000 lx	47%	50%	58%	61%	71%	77%	78%	81%
>2000 lx	48%	45%	37%	33%	25%	21%	18%	15%