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Window-to-Wall Ratio as a Mode of Daylight Optimization for an Educational Building with Opaque Double-Skin Façade

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Abstract

This study investigates the impact of Window-to-Wall Ratio (WWR) and Shading Coefficients (SC) as passive design strategies to optimise daylight in an opaque brick Double-Skin Façade (DSF) of an education building in Depok, Indonesia. A sample education building was simulated with DiaLux software for calculating the daylight distribution due to WWR on a daily basis during normal office hours. The optimum amount of window size and glazing were investigated for a typical floor plate area of 315.16m2. WWR was considered from 30% to 60% at 10% intervals in a horizontal and vertical expanding method of window. The simulations were performed in two sky conditions (sunny sky and standard CIE overcast sky) on different dates using glazing material of different SC. The primary findings of this study are that 40% WWR with SC 0.42 and 60% WWR with SC 0.95 achieve the best results for the north and south façade respectively of a DSF building.

Keywords: daylight performance, double skin façade, shading coefficient, window-to-wall ratio.

Introduction

The Department of Energy states that lighting consumes about 25% of all the electricity consumed by buildings and 40% by commercial buildings (IEA 2010; “Data & Statistics - IEA” n.d.). However, about half of all that electricity can be saved with the use of appropriate daylight strategies (Lechner 2015). A rational use of daylight significantly reduces the energy used for electric lighting (Burmaka et al. 2020). A study indicates that a 40% reduction in lighting energy consumption can reduce the overall energy consumption by 17% (Tsangrassoulis et al. 2017) Appropriate daylight strategies enable the capture and delivery of daylight deep inside interior spaces (Ullah 2019). For this reason, daylight should be considered as a replacement for electric light as well as the reduction of energy usage for lighting (IEA 2010). Electric lighting is a controllable man-made

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source that is easier to both study and engineer for achieving specific outcomes. Daylight however is a natural source that is more difficult to control considering its daily and annual dynamics, which produce different outcomes in different locations and weather conditions (Knoop et al. 2020).

Daylight admitted into interior spaces via building openings to replace or supplement electric lighting is used as a passive strategy to reduce energy consumption from electric lighting (Chi et al. 2018). Daylighting with appropriate window shape, size in terms of WWR, and glazing can also significantly reduce the need for electric lighting as well as provide comfort and energy savings in buildings (Alhagla et al. 2019; Zazzini et al. 2020). While high illuminance and colour identification provided by daylight enhance conditions for vision, it can also produce high luminance reflections on display screens and solar glare discomfort (Mahdavi et al. 2013). A study reports that the electrical energy used for lighting in the ASEAN countries (Indonesia, Malaysia, Philippines, Singapore, and Thailand) is about 20% to 24% of the total energy consumption in education buildings (Cammarano et al. 2015). Additionally, a study dealing with daylight in tropical areas indicates that most occupants prefer working under daylight (Hirning et al. 2017). Therefore, utilization of daylight in the context of energy savings also covers for visual needs ("Data & Statistics - IEA" n.d.; DiLaura and Houser 2011). However, most education buildings are dependent more on electric lighting despite the fact that energy savings between 20-70% can be achieved through daylight.

Double Skin Façade (DSF) plays an essential role in providing an environmental solution to climatic conditions where facades influence the daylight illuminance (Chi et al. 2018). DSFs are used as a passive strategy to moderate indoor conditions of hot climates (Zazzini et al. 2020). DSF as the outer skin with different materials ranges from fully glazed to opaque façades that absorb and reflect solar radiation (Barbosa and Alberto 2019). DSFs can minimize heat exchanges between the indoor and outdoor environments, thereby being useful in tropical climates (Halawa et al. 2018). The opaque external DSF layer works as a solar protection panel, which allows this application without shading devices (Barbosa and Alberto 2019).

As DSF usage might lead to a reduction of the quantity of daylight entering into space it is highly related to the window size (Moscoso et al. 2021). Daylight penetration from windows results in non-uniform spatial distribution of illuminance where high illuminance is experienced on areas next to openings, which then decreases progressively towards peripheral walls (Zazzini et al. 2020). The fenestration system should consider window shape, Window-to-Wall Ratio (WWR), and glazing type as higher WWR can provide higher illuminance and better daylight distribution within the room (Alhagla et al. 2019). Sometimes, even the shape and orientation of the glazing may lead to different WWR needs (Shameri et al. 2011; IEA 2010). Although lighting in a space via daylight penetration can be uniformly distributed with the appropriate use of WWR, inappropriately planned daylight can also become a source of excessive heat gain (Kontadakis et al. 2017).

Shading Coefficient (SC), which is defined as the solar radiation ratio with solar protection to solar radiation without solar protection, has been used to represent the solar shading performance of glazed areas (Gordon 2014; Lechner 2015). This implies that glazing materials and orientation play a significant role in providing broad daylight yet avoiding solar radiation that may increase energy usage. When daylight illuminates transparent materials, light is partially absorbed, reflected, and transmitted on both sides of the glazing surface (Liébard and Herde 2008). Due to these geographical differences, appropriate use of daylight can vary from sun and skylight exposure.

A study reports that daylight in tropical areas can be optimized when the WWR ranges between 25-35% without installing a DSF (Mahdavi et al. 2013). However, the average WWR required for a single-skin facade in tropical areas ranges between 25-50% (Pemerintah Provinsi DKI Jakarta 2012). Another study reports that the most optimum solution with the least mean distance to the utopia points is the combination of WWR 30%, wall reflectance of 0.8, and south orientation in tropical area (Mangkuto et al. 2016). WWR performances depend on numerous parameters such as window dimensions, external climatic conditions in terms of clear or overcast skies, and glazing materials (Zazzini et al. 2020; Lechner 2015). However the reasons for using daylight in architecture extend from those of a practical nature, including energy conservation, cost factors, and health and wellbeing, to those of a more intangible, aesthetic nature (Richard 2009). This study aims to investigate the impact of WWR and SC as passive design strategies to optimise daylight in an opaque DSF of an education building in Depok, Indonesia.

Methods

Research Framework

The research workflow and methodology applied in this study is by simulation using relevant software as shown in Figure 1. The simulations were conducted in DIALux software developed by DIAL on a model that represents the first-floor area of an educational building. DIALux utilizes radiosity as the simulation algorithm, which can be applied to validate lighting simulations that show very good agreement with the reference values in cases with a point source of light (Davoodi 2016; Mangkuto 2016). DIALux can easily and efficiently predict the daylight illuminance and its consequences in any building irrespective of its construction (Ahmad et al. 2020). The algorithm validation (Castillo-Martinez et al. 2017) and accuracy of prior versions of DIALux have been verified against the analytical test cases of CIE 1717:2006 (Mangkuto 2016). A study also concludes that DIALux 4.8 shows a margin of relative error lower than 30% in all case studies for Traditional and Standard CIE Overcast Skies (Acosta et al. 2015). Parametric modelling on existing data was conducted with parametric variables such as existing SC, WWR and sky condition to understand the existing condition without a reflective device to enable daylight further penetration into the room corner. After the initial data investigation, different scenarios are proposed with multiple combinations of SC and WWR to arrive at the most effective condition. The study limits its scope only to SC and WWR of DSF, hence other devices such as interior ceiling reflectors are not considered in the simulations.

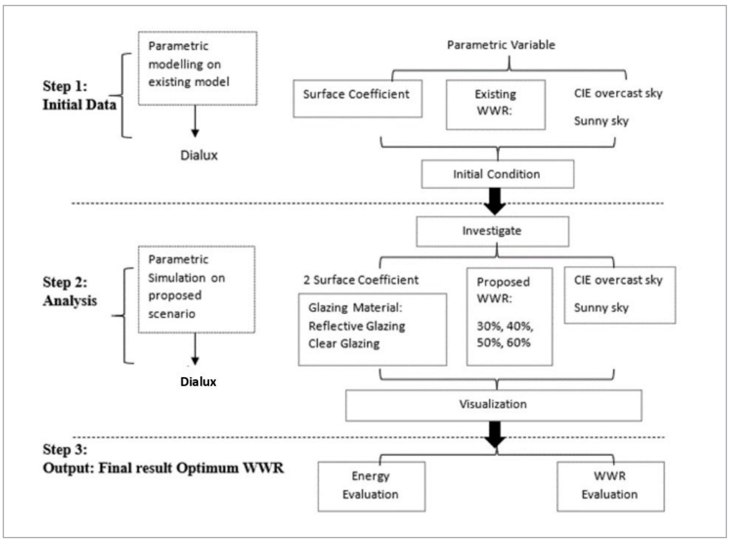


Fig. 1
Research framework: daylight optimization process and tools

Simulation Setting

The simulation model is based on an educational building with a secondary opaque facade built-in 2015, as shown in Figure 2. Opaque facade is used as the primary building material for the facade to prevent excessive heat gain and act as a shading device. Within this study, five stories of secondary opaque facade models with different orientations, window to wall ratio percentages, and different light transmittance glass were used. Each opaque module is 10m^2 with spaces about 0,277 m among each module to let the daylight in. Between the wall and the secondary facade, there is an unconditional space of 1.35m in Figure 3.

According to the sun path diagram in Indonesia, sun position will change every half a year in the north and south side periodically as shown in Figure 3. Therefore simulation runs were carried

Fig. 2

Nano technology laboratory for higher education in Depok, Indonesia

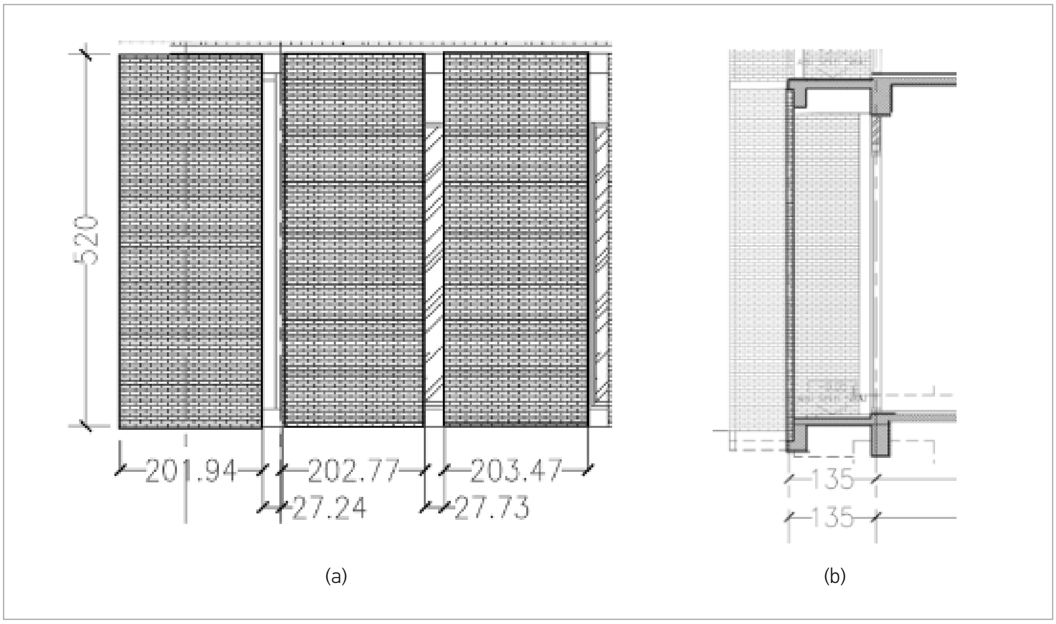


Fig. 3

Façade Details: (a) Elevation (b) Section

out for Depok (357°N, 6° 21' 41' ' S and 106°49'30" E) at 10 am on 21st March, 21st June and 21st December with two models facing north and south facade based on its sun path as shown in Figure 4. Additionally the dynamic nature of the Indonesian sky causes daylight conditions to change rapidly in a short span of time. Therefore each model was simulated under two different skies: the standard CIE overcast sky and sunny sky, during summer and winter solstice with several WWR and glazing SC in north- and south-facing facade orientations. Tropical areas typically receive long sun hours and massive amounts of daylight throughout the year, where each direction can receive equal amounts of light as others: a north window can receive as much light as a south window (Lechner 2015). The typical floor plate used in this simulation is the first floor focusing on two areas: the north-facing floor with an area of 164.2m^2 and the south-facing floor with an area of

150.96m², as shown in Figure 5. Single glazing material with clear SC 0.95 and reflective SC 0.42 are used in this study since it has a secondary facade with a 1.3m gap to reduce solar radiation between its skin to absorb, reflect and transmit daylight. These two glazing materials are based on Jakarta's Governor Regulation No. 38/2012 Vol.1 (Pemerintah Provinsi DKI Jakarta 2012).

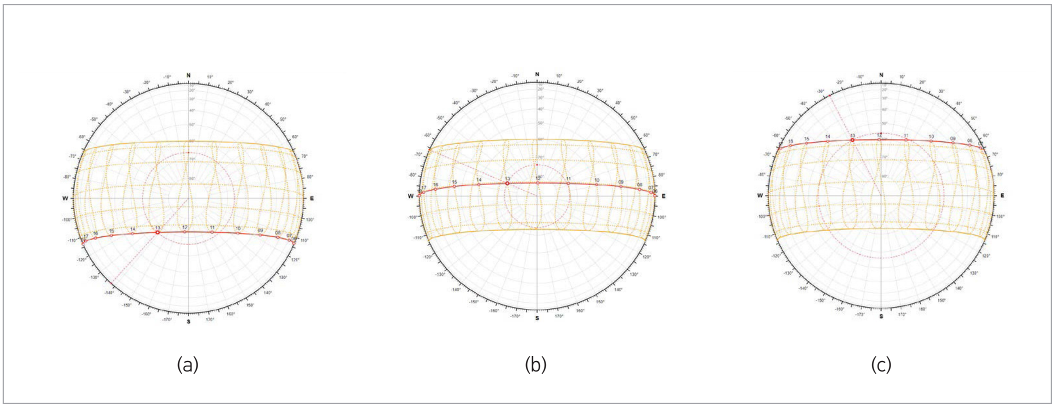


Fig. 4

Sun path diagram on a) December 21st, b) March 21st, and c) June 21st at 13am

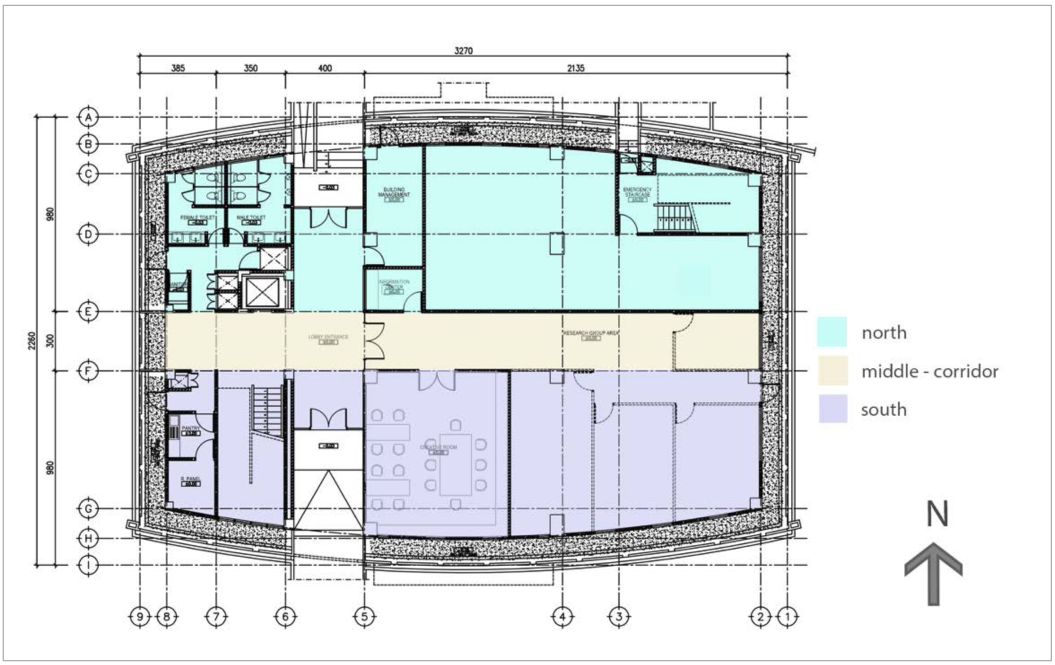


Fig. 5

First floor layout plan from the selected model comprising laboratories and meeting room with total area of 315.15m²

Table 1

Calculated building parameters

Parameter	Ceiling height (m)	Wall thickness (m)	Surface reflection coefficient of ceiling / wall / floor
Value	3.8	0.12	0.7 / 0.5 / 0.1

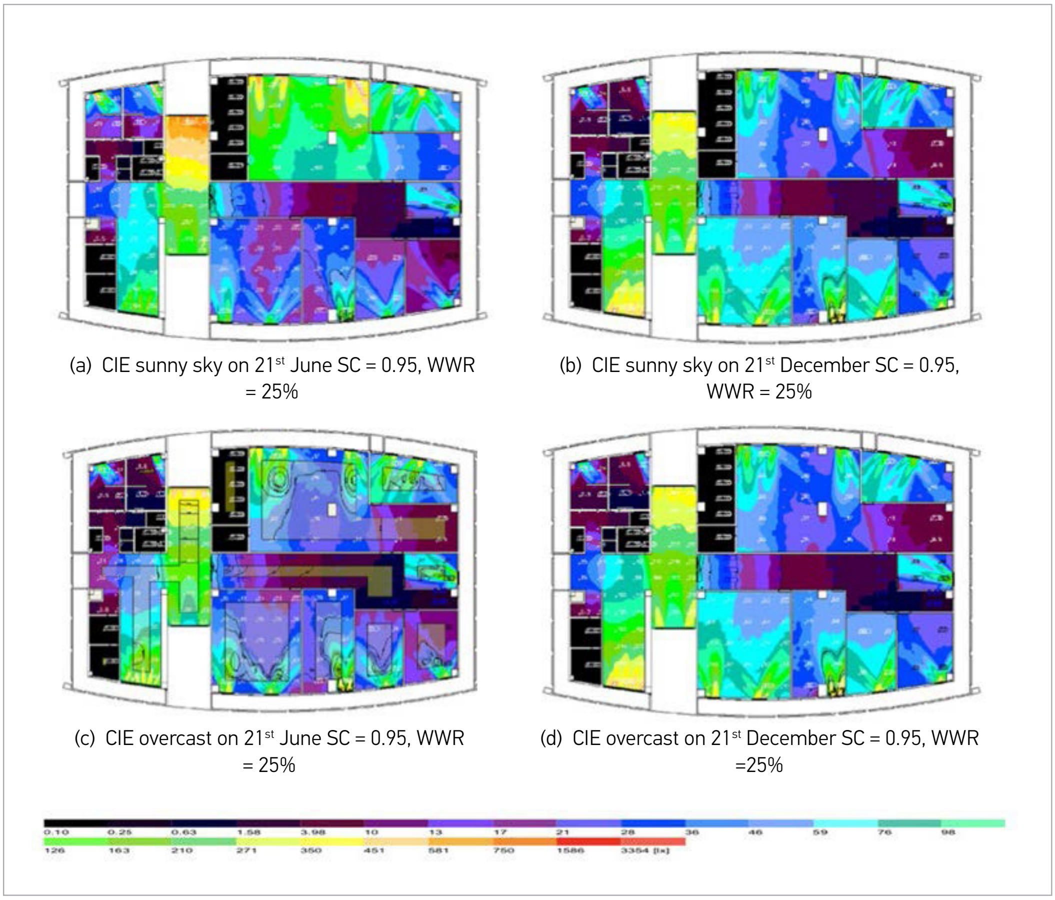
A series of simulations using DIALux software were performed in two sky conditions (CIE overcast sky and sunny sky) with height calculation parameter of 0.8m and setting of the area as shown in Table 1. The outcomes acquired from 32 simulations were analysed and categorized as shown in Table 2. According to Indonesian National Standard (SNI), average illuminance (E_{Avg}) of 250 lux was considered for a visual task carried out in educational buildings and 500 lux for a laboratory (SNI 2004). The amount of daylight received was classified based on user-defined illuminance threshold intervals of three categories such as insufficient if less than 250 lux, sufficient if in the range of 251-500 lux, and excessive if more than 500 lux.

Results

The first sets of simulations were performed using the existing building condition. In order to determine the optimum percentages of SC and WWR, at first both north and south facades were considered 25% as per the existing condition and the daylight illuminance was determined. Then the percentage of WWR was changed starting from 30% up to 60% with a 10% step interval (Shaeri et al. 2019). The lower limit was set at 30% WWR considering the fact that the existing building with 25% WWR had low daylight penetration. The upper limit was set at 60% WWR to avoid glare and heat gain from excessive daylight. The second sets of simulation were conducted using single glazing materials of clear SC 0.95 and reflective SC 0.42. The results were then compared based on the WWR effects under the sunny sky and CIE overcast sky for daylight optimization.

Existing Condition

The simulation result for the existing condition performed under a sunny sky and CIE overcast sky show that despite 25% WWR with single glazing of SC 0.95, daylight penetration was low due to the secondary facade influence. The illuminance on both north- and south-facing sides of the floor do not meet the required minimum standards for E_{Avg}, as shown in **Figure 6**, and **Table 2**. Studies reveal that simulated values of E_{Avg} for overcast skies can vary considerably due to the refraction and scattering of daylight (Kondáš, and Darula, 2014; Kensek and Suk, 2011).



(a) CIE sunny sky on 21st June SC = 0.95, WWR = 25%

(b) CIE sunny sky on 21st December SC = 0.95, WWR = 25%

(c) CIE overcast on 21st June SC = 0.95, WWR = 25%

(d) CIE overcast on 21st December SC = 0.95, WWR =25%

Fig. 6

Daylight simulation for existing condition

Table 2

Existing scenario with SC 0.95 and 25% WWR

SC – Orientation	WWR	E_{Avg} Overcast (lx)			E_{Avg} Sunny (lx)		
		March	June	Dec	March	June	Dec
0.95 – North	25%	69.1	85.9	94.2	46.9	628	71.6
0.95 – South	25%	70.9	99	109	278	772	182

Proposed Conditions

The simulation results using different WWR with SC 0.42 as shown in **Figure 7** and **Table 3**, and SC 0.95 as shown in **Figure 8** and **Table 4** vary due to the tropical sun path e.g. E_{Avg} lowering at 35% WWR and reaching excessively high levels for the north orientation. Under the sunny sky condition, the E_{Avg} achieved with SC 0.42 on north-facing floor in June with 60% WWR is 473.7 lux meeting the comfortable standard. However, the south-facing floor is not able to meet the illuminance standard even with 60% WWR. Conversely, under CIE overcast sky conditions the E_{Avg} achieved do not meet the minimum standards under any WWR.

Table 3

Proposed scenarios with SC 0.42 and different WWR

SC – Orientation	WWR	E_{Avg} Overcast (lx)			E_{Avg} Sunny (lx)		
		March	June	Dec	March	June	Dec
0.42 – North	30%	45.4	41.7	45.7	51.4	331	34.9
	40%	138	122	130	126	506	98.6
	50%	149	129	142	145	609	107
	60%	157.9	156.6	162	163.4	731	147
0.42 – South	30%	65.8	49.2	54	59.7	38.7	85.2
	40%	136	120	129	125	484	98.1
	50%	163	141	155	129	511	241
	60%	171.6	170	176	164.1	554.9	248

Fig. 7

Comparison of E_{Avg} a) north orientation and b) south orientation with SC 0.42

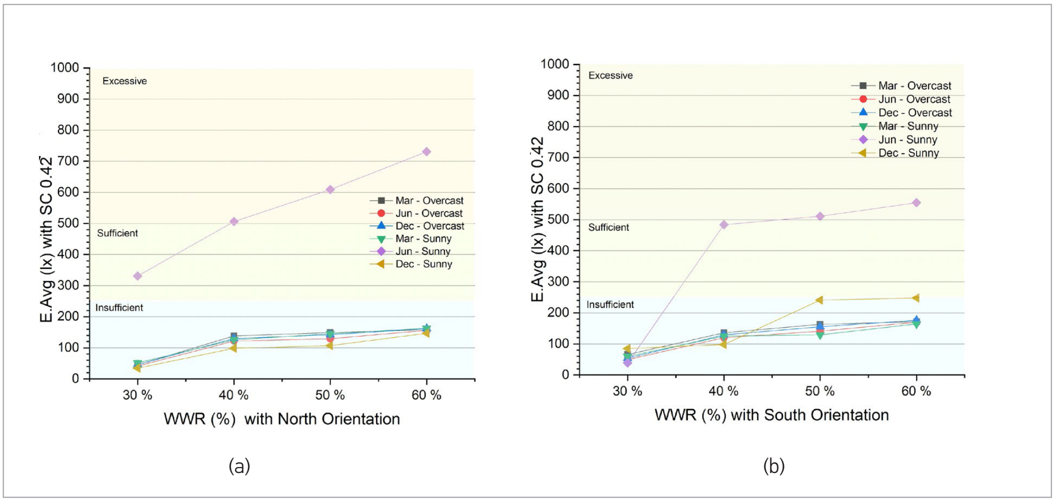


Table 4

Proposed scenarios with SC 0.95 and different WWR

SC – Orientation	WWR	E_{Avg} Overcast (lx)			E_{Avg} Sunny (lx)		
		March	June	Dec	March	June	Dec
0.95 – North	30%	106	92.4	101	106	728	77.1
	40%	137	121	130	134	506	98.6
	50%	149	129	142	145	913	107
	60%	140	122	134	136	934	101
0.95 – South	30%	122	106	117	97.3	83.1	195
	40%	151	134	144	120	104	213
	50%	163	141	155	129	111	241
	60%	183	159	175	147	126	287

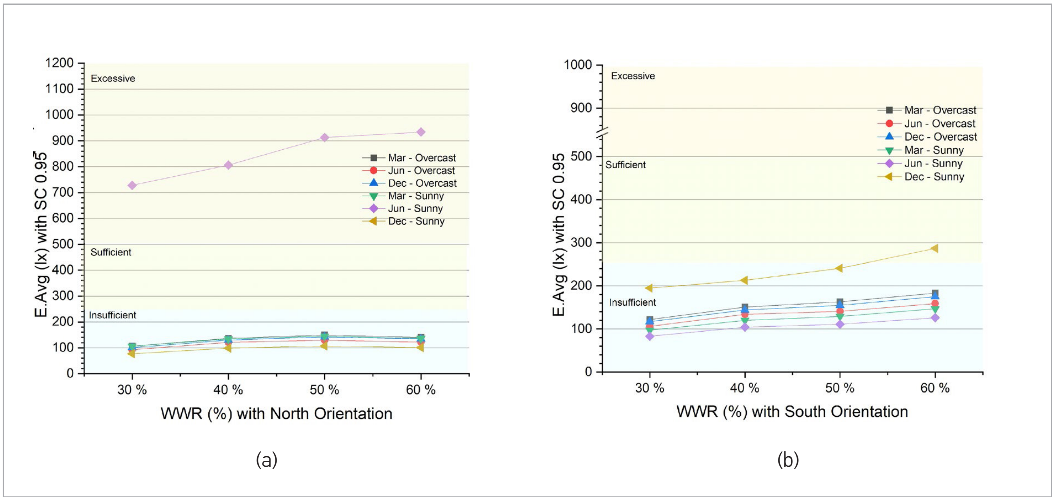


Fig. 8

Comparison of E_{Avg} a) north orientation and b) south orientation with SC 0.95

Under the sunny sky condition, the E_{Avg} achieved with SC 0.95 on the north-facing floor in June for most WWR are in excess of 900 lux thereby causing glare. However, on the south-facing floor in December with 60% WWR, this material provides 154 lux, which is insufficient for the user as shown in **Figure 8**. Conversely, under CIE overcast sky conditions with 60% WWR, the highest E_{Avg} achieved is 176 lux on the south-facing floor during December, while on the north-facing floor it is 162 lux. Both these outcomes do not provide sufficient illuminance for the user.

Discussion

As investigated and documented in this study, the E_{Avg} in an existing education building with an opaque DSF having 25% WWR do not meet sufficient illuminance standards. Therefore, various combinations of SC and WWR have been applied by simulation to arrive at the most suitable fenestration detail for a building with an opaque DSF. **Table 5** shows the results of a proposed mixed-use scenario of glazing and WWR. A 40% WWR is more effective for daylight optimization on the north-facing facade during sunny sky conditions because it produces less direct glare compared to WWR 50% and 60%. Similarly, a 60% WWR is more effective for daylight optimization on the south-facing facade during overcast sky conditions as it maximises the amount of daylight entering the space. Application of reflective glazing with SC 0.42 on the north-facing facade produces more uniform daylight and recorded 506 lux in June. Application of clear glazing with SC 0.95 produces more uniform daylight on the south-facing facade and recorded 126 lux in June. Therefore, the following mixed usage combination of clear and reflective glazing materials along with WWR is proposed to optimize the building's effective exposure to the sun:

- North-facing facade – 40% WWR with reflective glazing SC 0.42
- South-facing facade – 60% WWR with clear glazing SC 0.95

The above results support the study (Nordin et al. 2019) that although a higher range of WWR with 40% at north-facing facade and 60% at south-facing facade may produce glare, the secondary facade is able to filter excessive light radiation and consequent heat gain. However, supplemental electric lighting will be required in this building to meet the minimum illuminance standard especially during overcast sky conditions. This shows that although SC and WWR can mitigate

Table 5

Proposed scenario with mixed-usage of SC and WWR

SC – Orientation	WWR	E_{Avg} Overcast (lx)			E_{Avg} Sunny (lx)		
		March	June	Dec	March	June	Dec
0.42 – North	40%	138	122	130	126	506	98.6
0.95 – South	60%	183	159	175	147	126	287

lighting-related energy requirements, education buildings still have to depend on supplemental electric lighting. Additionally, although window height is important to provide a higher illuminance (Sánchez-Tocino et al. 2019), in case of different heights of room and materials used for the secondary façade, the outcome may vary.

Conclusions

Architects and planners in order to reduce energy gain from sun radiation generally tend to use fenestration details that at some point can block daylight out completely. This study shows that secondary opaque DSFs with an appropriate combination of SC and WWR can be used as a fenestration detail in tropical climatic conditions to optimize daylight and reduce energy usage along with adding to reasons of aesthetics, health and wellbeing. Daylight can be creatively harnessed with a fenestration detail that combines SC and WWR to improve the aesthetics and energy performance of buildings. However, daylight cannot be used as a sole source of illumination even in tropical regions as this study shows that supplemental illumination might be required in the form of electric lighting during certain times of year. Additionally, it is important to note the various limitations of this study: firstly, the generalizability of this study requires further exploration; secondly, this study limits the interference of human behaviour towards lighting use that may impact its energy use; thirdly, other external factors that may interfere with the amount of daylight received were not considered in this study. Therefore further research is required in other types of secondary facades that will provide further guidance for daylight design in tropical areas.

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