Article

Design Optimisation of Fixed and Adaptive Shading Devices on Four Façade Orientations of a High-Rise Office Building in the Tropics

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Abstract: Optimisation of shading devices in buildings is a broadly investigated topic; however, most studies only focus on a single façade orientation, since the observed buildings are typically located in high latitude regions. However, in tropical regions, optimisation of all façade orientations is required due to the relatively high solar radiation and long sunshine duration. While adaptive shading devices are a promising solution, they are not without disadvantages, and as such a combination of adaptive shading devices and a fixed shading device shall be considered. This research therefore aims to design the optimum internal shading devices on four façade orientations of a high-rise office building in a tropical city, considering fixed and adaptive shading design options, and to determine the impact on annual daylight performance using computational modelling and simulation. The simulation is carried out under: (1) fixed design option, focusing on the numbers and width of slats; and (2) adaptive design option, focusing on the slat angle on various conditions. It is found that both $sDA_{300/50\%}$ and $ASE_{1000,250}$ are only influenced by the orientation. Under the fixed design option, the $sDA_{300/50\%}$ and $ASE_{1000,250}$ targets can be achieved only on the north and south façades, and accordingly the adaptive design option shall be implemented on the east and west façades. Overall, this study contributes to knowledge regarding the optimisation of shading devices in high-rise buildings in the tropics, considering the daylight admission from the four cardinal orientations.

Keywords: shading device; daylighting; high-rise building; adaptive façade; tropical region

1. Introduction

Daylight through windows in office buildings is believed to yield positive impacts on the productivity of the employees [1–3]. It has been proposed that occupants' productivity is correlated with their motivation and satisfaction levels, which can be increased by maximizing daylight and visual access to the windows, revealing information, such as weather, time, surrounding activities, and nature dynamics [4,5]. It is well understood that daylight in buildings creates a connectivity between outdoor and indoor spaces, providing visual comfort to the occupants [3,5,6].

In the practice of building design and operation, daylighting is also critical in determining the overall building energy demand, since more daylight penetration means not only smaller electric lighting energy demand [7–10], but also greater heating and cooling energy demands [11–14]. In non-tropical regions, during winter, daylight penetration, particularly direct sunlight penetration, may increase heat gain in buildings via radiation. However, daylight is typically admitted through windows, which will also result in heat loss due to conduction. The net effect typically results in heat loss, which in turn increase the heating energy demand. In tropical regions, heating energy demand is irrelevant, and daylight is only associated with cooling energy demand. In any case, to obtain a balanced performance, the use of solar control or shading devices in office buildings is practically recommended or even mandatory to obtain green building ratings or certifications [15,16].

Due to its critical role in building design and operation, the optimisation of shading devices in office buildings has long become a broadly investigated topic. The integration of such devices with the building façades is one of the key issues in this area, including among others the design and implementation of moveable or non-stationary shading devices. The terms ‘adaptive’ or ‘climate adaptive’ façades or building shells have been coined in the literature [17–21], as well as alternative adjectives, such as ‘intelligent’ [22–24], ‘kinetic’ [24–30], ‘dynamic’ [31–33], ‘responsive’ [34], ‘active’ [35], and many others. All of these terms refer to a façade system that may adapt or respond to changes in climate factors in the outdoor environment, in order to maintain or improve the building’s performance of the indoor space. Exploratory surveys on stakeholders related to adaptive façades [19,36] suggest that environmental and/or building performance and occupant well-being or comfort indicators due to the installation and operation of adaptive façades are yet to be assessed properly, because there exist other priorities, which results in the technology not being implemented to its full extent [19].

Most studies on façade optimisation, however, only focus on a single façade orientation, which is the equator-facing side, because the observed buildings are typically located in high latitude regions, e.g., [37–41]. Meanwhile, in tropical regions, optimisation of all façade orientations is required due to the relatively high solar radiation and long sunshine duration. Tropical cities commonly observe an average annual solar diffuse irradiance of 400–500 W/m², with a peak solar direct irradiance of around 1000 W/m² [42,43], which may lead to overheating problems in buildings, particularly near the east and west façades [43,44]. However, it is not always possible to avoid having façades on these orientations; thus, creative improvement and optimisation are required nonetheless [43,45].

A thorough review on the design optimisation of shading devices in tropical office buildings is available in the literature [43]. Some studies focus on fixed (or static) shading devices [44–51], while some focus on adaptive (or any of the alternative adjectives) shading devices [52–55]. It is concluded that there is still a lack of studies on adaptive shading devices on office buildings façades in the tropical context [43].

In addition to the main conclusion of the review [43], it is also mentioned that fixed shading devices have been a popular choice for application in the tropics, particularly to optimise thermal and daylight performance, despite the limitation in responding to the varying weather conditions. Meanwhile, adaptive shading devices are less popular than fixed devices, mainly due to the complexity and the attributed operational costs [43]. Similar lists of disadvantages and limitations of adaptive façades have been also reported for the European context [19]. A hybrid system combining both fixed and adaptive shading devices is therefore recommended, among other possibilities, as a compromise.

Therefore, this research aims to design the optimum (internal, horizontal) shading devices on the four façade orientations of a high-rise office building in a tropical city, considering fixed and adaptive shading design options, and to determine the impact on the annual daylight performance of the building. The objectives are to reach optimum values of annual daylight metrics, namely the spatial daylight autonomy (sDA_{300/50%}) and annual sunlight exposure (ASE_{1000,250}) in the highest floor of the observed building, under fixed and adaptive shading design options. Computational building performance

modelling and simulation is proposed to be the main tool to achieve the objectives. As an indicator for glare, this study employed $ASE_{1000,250}$, since several studies in the literature suggested that the metric is consistent with visual comfort indicators, such as DGP and UDI-e [55,56]. Furthermore, when those criteria are met, the design can reflect the potential for both energy saving and visual comfort inside the space [15].

The article is structured as follows. Section 2 describes the methods, Sections 3 and 4 provide the results and discussion, and Section 5 concludes the article.

2. Methods

This study focuses on optimising internal, horizontal shading devices that are expected to provide a uniform and well-distributed daylight illumination in interior spaces [12,37,40,51,57]. A predetermined, newly designed office building in Jakarta, Indonesia ($6^{\circ}12' S$, $106^{\circ}49' E$, tropical monsoon (Am) climate type), is taken as the case study. The building is intended to occupy a $57 m \times 36 m$ site area, with a total gross floor area of $73,000 m^2$, comprising 35 stories with total building height of 142.8 m (Figure 1). The typical floor plan and section views of the office space are displayed in Figure 2.

Figure 1. (a) Elevation (long section), (b) elevation (short section) and (c) bird-eye view of the observed building.

Three scenarios are to be considered for the modelling and simulation in this study. These are the: (1) baseline scenario: involving no shading devices; (2) fixed shading design options: involving fixed element of horizontal shading devices (venetian blinds); and (3) adaptive shading design options: involving adaptive component and sensor on the horizontal shading devices.

(a)

(b)

(c)

Figure 2. (a) Typical floor plan, (b) long section view, and (c) short section view of the office space.

Following the recommendation in LEED v4 [15], two daylight metrics, namely the $sDA_{300/50\%}$ and $ASE_{1000,250}$, are observed in the simulation. The $sDA_{300/50\%}$ is defined as the percentage of the occupied floor area that has daylight autonomy with a minimum illuminance threshold of 300 lx (DA_{300}) for at least 50% of the time in the entire year. Meanwhile, the $ASE_{1000,250}$ is defined as the percentage of the occupied floor area receiving direct sunlight illuminance (E_D) above 1000 lux in at least 250 h during the entire year, so that:

$$sDA_{300/50\%} = \frac{A_{DA_{300} \geq 50\%}}{A_{total}} \times 100\% \approx \frac{n_{DA_{300} \geq 50\%}}{n_{total}} \times 100\% \quad (1)$$

$$ASE_{1000,250} = \frac{A_{E_D \geq 1000lx, 250h}}{A_{total}} \times 100\% \approx \frac{n_{E_D \geq 1000lx, 250h}}{n_{total}} \times 100\% \quad (2)$$

where A_{total} denotes the total floor area and n_{total} denotes the total number of sensor points on the floor or workplane area.

Provided the compulsory existence of glare control or shading devices, the target of $sDA_{300/50\%}$ for office and other typical commercial (except healthcare) buildings is a minimum of 55% [15]. Meanwhile, the original target of $ASE_{1000,250}$ was a maximum of 10%, but in the revised version of LEED v4, it has been relaxed to become 20% [15]. This study is conducted to evaluate the daylight metrics performance of the given building according to LEED v4 standard; thus, glare will be estimated using the $ASE_{1000,250}$ parameters.

The simulation was conducted in using *Ladybug* and *Honeybee Legacy* plug-ins in *Grasshopper*. These plug-ins utilize *Daysim* as the simulation engine, with ambient parameters, as shown in Table 1. The locations of the sun in *Daysim* implementation are at around 65 locations in the sky for the entire year. *Daysim* is a *Radiance* derivative, which takes the geometrical model from *Radiance* through its *radfiles2daysim* function for conducting annual daylight simulation [58]. Thus, the parameters to conduct the $sDA_{300/50\%}$ and $ASE_{1000,250}$ simulation in *Daysim* as shown in Table 1 are based on the recommended settings for accurate computation in *Radiance*. Notice that since only direct sunlight is considered for $ASE_{1000,250}$, the ambient bounce (ab) parameter in the *Radiance* simulation for that metric is set as zero.

Table 1. *Radiance* simulation parameters.

Metric	ab	ad	ar	as	aa	lw
$sDA_{300/50\%}$	6	1000	20	300	0.1	0.004
$ASE_{1000,250}$	0	1000	20	300	0.1	0.004

The *Grasshopper* definition and its main simulation workflow in this study is depicted in Figure 3. In general, the simulation definition in this study consists of seven main parts. The first part is the modelling, where the *Grasshopper* parameters take input from *Rhinoceros* geometry and convert them into the *Honeybee* model. The second part is the setting for building materials, which for this case is shown later in Table 2. The third part is modelling and setting parameters for the shading devices. This step is omitted for the baseline scenario, since the shading devices are not applicable. The fourth part is defining the parameters and components for selecting the weather file, sensor and defining the simulation recipe. The fifth part is assigning the component to run the simulation. In the sixth part, after the simulation finishes, the results are read, and the data are finally exported into a CSV file in the seventh part for further analysis. More detailed explanations considering specific simulation requirements and procedures are provided in the following subsection.

Figure 3. Grasshopper definition and its main simulation workflow.

Table 2. Radiance material properties of various surfaces in the model.

Surface	Reflectance (-)			Specularity (-)	Roughness (-)
	R	G	B		
Ceiling	0.80	0.80	0.80	0	0
Exterior wall	0.40	0.40	0.40	0	0
Interior wall	0.75	0.75	0.75	0	0
Floor	0.20	0.20	0.20	0	0
Metal shading	0.40	0.40	0.40	0.90	0

2.1. Baseline Scenario

The first stage of the simulation is carried out using a model of the building without any shading devices. The building model is constructed in *Rhinoceros 3D*, where the *Radiance* material properties of the relevant surfaces are summarised in Table 2. The glazing component is set to have a visual transmittance of 0.75 and refractive index of 1.52. The shading (slat) material is assigned to be of metal surface with a relatively high specularity, up to 0.90, as found, for instance, in brushed or polished aluminium [55,59]. In this study, the window-to-wall ratio (WWR) is fixed to 50%, according to the preliminary design of the building.

The simulation is also carried out by dividing the sampled floor, which is the 35th (highest) floor, into four zones, namely the north, east, south and west zones (Figure 4). All of the simulation processes are conducted in *Grasshopper* using additional plug-ins, such as *Honeybee* and *Ladybug*, while the optimisation of the shading devices properties is conducted using iterations from several *Grasshopper* simulation. As the simulation is conducted on the highest floor of the building, it can be assumed that there is little to no impact of the surrounding buildings or objects that may cause external reflection into the building space, so that the relation between the input and output variables can be better understood. Moreover, in typical high rise buildings in Indonesia, the rent office spaces are mostly located in the upper floors, whereas the lower floors are typically reserved for non-office spaces.

Figure 4. Illustration of the four sampled zones of the office space to be simulated.

2.2. Fixed Shading Design Option

In the fixed shading design option, horizontal shading devices (venetian blinds) are introduced on the internal side of the façades. The default material of the slats is metal with a reflectance of 0.5 and a specularity of 0.9. The simulation is conducted by varying the width of the slats, as well as the distance between the adjacent slat rows (Figure 5), assuming a constant, net opening height of 3 m (cf. Figure 2). The required number of slats for each façade in zone is then reported, which is equal to 8.75 m divided by the slat width, rounded to the nearest integer value.

Figure 5. Illustration of modelled fixed horizontal shading device.

The simulation is carried out using the *Ladybug* and *Honeybee* function in *Grasshopper*, for four sampled zones of the office space (cf. Figure 4).

2.3. Adaptive Shading Design Option

In the adaptive shading design option, the horizontal shading devices are modelled with adaptive properties in terms of varying slat angles, responding to the daylighting condition, which is represented with the indoor illuminance. In this design option, the slat angles are varied simultaneously within the range of -45° to 45° with a step of 5° (Figure 6). The slats are thus never entirely closed (90° angle), but are only half open, either up or down.

Figure 6. Illustration of the modelled adaptive horizontal shading devices.

The average workplane illuminance (E_{av}) in each office zone is computed and assigned as the reference for changing the slat angles. The obtained E_{av} data for the entire year are then divided into four scenarios (k_1 , k_2 , k_3 , and k_4), based on the threshold values of 500, 1000, and 2500 lx. In other words, when $E_{av} < 500$ lx, scenario 1 (k_1) applies. Scenario k_2 applies when $500 \text{ lx} \leq E_{av} < 1000$ lx, k_3 when $1000 \text{ lx} \leq E_{av} < 2500$ lx, and k_4 when $E_{av} \geq 2500$ lx. The *EnergyPlus* weather file (EPW) data of the location is then limited to daytime periods in the entire year, to allow different optimum outcomes in each scenario (k_1 until k_4). In this way, the optimum slat angle for each scenario and for each sampled zone can be obtained and reported. For conducting the simulation, the EPW file is automatically extracted into a compatible file format for *Daysim* simulation using the embedded function in *Ladybug* and *Honeybee*.

Furthermore, optimisation of the slat angle is carried out for the critical zones in which the $ASE_{1000,250}$ particularly exceeds the maximum criterion. To ensure that the variation affects both $sDA_{300/50\%}$ and $ASE_{1000,250}$ values, sensitivity analysis is conducted with respect to the slat angle in all working hours throughout the year, using a grid-based simulation recipe from the *Honeybee* plugin in *Grasshopper*. Grid-base simulations are conducted on 21 June, 21 March, and 21 December, when the sun's apparent position is respectively at the extreme north, centre, and south.

After the sensitivity analysis is conducted, further simulation is carried out using the assigned EPW file to achieve the optimum slat angle for each scenario. The *Colibri* toolbox is employed to perform the iteration and to record the simulation data into a CSV file. To determine the optimum angle, optimisation is performed by sorting all possible combinations and by finding the combination with $sDA_{300/50\%}$ and $ASE_{1000,250}$ that have the least distance to (100%, 0%) in each scenario. In this study, the genetic algorithm (GA) is not particularly applied, since the observed combinations are rather limited, so that performing a GA optimisation would be inefficient. The conducted optimisation method

was preferable for being computationally inexpensive since the simulations were run on machine with an Intel® Core™ i3 processor.

3. Results

3.1. Baseline Scenario

Simulation results of the baseline scenario (without any shading devices) is displayed in Figure 7, for all sampled zones. It is observed that $sDA_{300/50\%}$ in almost all cases have satisfied the criterion ($\geq 55\%$), while all $ASE_{1000,250}$ values exceed the maximum target of 20%.

Figure 7. Annual simulation results in the baseline scenario.

The $ASE_{1000,250}$ in the east and west zones are around 2–3 times greater than those in the north and south zones. This is because north and south orientations in the tropics are exposed very little to direct sunlight, while east and west orientations are clearly exposed to direct sunlight in the morning and late afternoon, respectively. However, despite having greater $ASE_{1000,250}$, the east and west zones have smaller $sDA_{300/50\%}$ values (around 70%) compared to the north and south zones (which have around 90%). This is because, during the day, the sun's relative position is either at the north or the south of the building and at high altitude angles, so that the diffuse daylight illuminances in the north and south zones are maximized while the direct daylight illuminances are kept to a minimum. Meanwhile, the direct sunlight contribution is relatively high in the east and west zones, but only for a short period in the beginning and towards the end of the day.

It is also noticed that the $sDA_{300/50\%}$ in the north zone (around 92%) are slightly greater than those in the south zone (around 87%), because the building is located slightly at the south of the equator (6° S). Moreover, the sun is at the north in the middle of the year (June until August), which also coincides with the dry season; while the sun is at the south in the beginning and end of the year (January, February, December), which coincides with the wet or rainy season. As a result, the $ASE_{1000,250}$ in the south zone are only half of those in the north zone (22% compared to 40%), and while having only slightly lesser $sDA_{300/50\%}$, the south zone generally performs better than the north zone, as also suggested in the literature [10].

Overall, from the baseline scenario results, it can be concluded that shading devices are practically required in the east and west zones, particularly to reduce the direct sunlight penetration in the morning and late afternoon.

3.2. Fixed Shading Design Option

In the fixed shading design option, iterations are performed to find the optimum number of slats. The optimum numbers are taken from the iteration with the maximum value of $(sDA_{300/50\%} - ASE_{1000,250})$. The results for each zone are shown in Table 3. It is found that the north, east, and west zones require as many as 30 slats, i.e., 100 mm wide each. Meanwhile, the south zone only requires 28 slats, i.e., 107 mm wide each. Again, the lower requirement for the south zone can be attributed to the relatively small $ASE_{1000,250}$ values, as found in the baseline scenario.

The iteration results are shown by the scatter plots in Figure 8, which indicate that the number of slats may result in a wide range of $ASE_{1000,250}$, up to approximately 10% in most orientations. However, the number of slats seems to only slightly affect the $sDA_{300/50\%}$.

Figure 8. Cont.

Figure 8. Scatter plots of the $sDA_{300/50\%}$ and $ASE_{1000,250}$ due to number of slat variation each direction.

Table 3. Optimum number of slats in the fixed shading design option.

North	West	South	East
30	30	28	30

The annual daylight simulation results in the fixed design option, using the optimum number of slats as in Table 3, are displayed in Figure 9. It is observed that $sDA_{300/50\%}$ in the north and south zones have now reached or are very close to the maximum values of 100. Meanwhile, $sDA_{300/50\%}$ in the east and west zones increase by approximately 6% to become 74–77%, thus satisfying the minimum criterion of 55%.

Regarding $ASE_{1000,250}$, the values at all sampled zones have been reduced to become roughly half the values in the baseline scenario. The $ASE_{1000,250}$ in the north and south zones are now smaller than the maximum target of 20%, but the values in the east and west zones (38%) still exceed the target. Therefore, the proposed fixed design option can be applied for the north and south zones, but not for the east and west zones. In that case, the adaptive design option shall thus be considered.

Figure 9. Annual simulation results in the fixed shading design option.

3.3. Adaptive Shading Design Option

The results in Section 3.2 suggest that the adaptive shading design option should be considered in the east and west zones. The time series of the average workplane illuminance in the east and west zones for the entire year are displayed in Figure 10. The maximum value of the average workplane illuminance in the east zone is approximately 8000 lx, whereas in the west zone the maximum value is approximately 4800 lx.

(a)

(b)

Figure 10. Time series of the average workplane illuminance in the (a) east and (b) west zones, and the resulting scenarios k_1 until k_4 .

The relations between the slat angle and time with respect to $sDA_{300/50\%}$ in the east and west zones on the three critical days are displayed in Figure 11, while those with respect to $ASE_{1000,250}$ are displayed in Figure 12. Both figures suggest that in the east zone, scenario k_4 applies in the beginning of the day (8.00 h) on 21 March and 21 June, and practically all parts of the zones have exceeded the workplane illuminance of 300 lx. Scenario k_3 applies from 9.00 h, or from 8.00 h on 21 December, until noon. From noon until the end of the working day, scenario k_2 or k_1 applies. The opposite trend applies to the west zone, in which scenarios k_1, k_2, k_3, k_4 apply in that order as the day goes by.

Figure 11 indicates that the daylight availability, represented by the spatial distributions of DA_{300} , on 21 June is generally the greatest among the three observed days, as it corresponds to the dry season in that location, which is characterized by relatively low precipitation. At the beginning of the day in the east zone, the incoming daylight penetration is excellent enough that changing the slat angle within any value between

-45° and 45° shall yield $sDA_{300/50\%}$ between 70% and 100%, but not less. On 21 June, the variation of slat angle corresponds to lower uncertainty of $sDA_{300/50\%}$, compared to that on 21 December, again due to the relatively high amount of solar radiation in the middle of the year.

Similar tendencies are also observed on the $ASE_{1000,250}$ at both orientations (Figure 12), even though the differences between $ASE_{1000,250}$ variation on the three days are less obvious than those for $sDA_{300/50\%}$. It can however be observed that the negative slat angles correlate with a greater proportion of direct illuminance on the workplane, which approaches 30%. In the east zone, the $ASE_{1000,250}$ is practically zero, regardless of the slat angle, from 11.00 h onwards; approximately two-thirds of the time. Conversely, regardless of the slat angle, the $ASE_{1000,250}$ in the west zone is also zero, from 8.00 until 14.00 h, which is about two-thirds of the time.

Figure 11. Relations between slat angle and time with respect to $sDA_{300/50\%}$ in the east and west zones on 21 March, 21 June, and 21 December.

Figure 12. Relations between slat angle and time with respect to $ASE_{1000,250}$ in the east and west zones on 21 March, 21 June, and 21 December.

In the east zone, glare risk is likely to occur in the morning, particularly in around March–September, when the sun’s relative position is north of the equator. The opposite applies to the west zone, where glare can be expected in the afternoon, particularly around October–February.

The scatter plots of the partial $sDA_{300/50\%}$ and $ASE_{1000,250}$ due to slat angle variations in all scenarios, respectively for the east and west zones, are displayed in Figures 13 and 14.

Figure 13. Scatter plots of the $sDA_{300/50\%}$ and $ASE_{1000,250}$ due to slat angle variation in the east zone, for (a) all scenarios, (b) scenario k_1 , (c) k_2 , (d) k_3 , (e) k_4 .

Figure 14. Scatter plots of the $sDA_{300/50\%}$ and $ASE_{1000,250}$ due to slat angle variation in the west zone, in (a) all scenarios, (b) scenario k_1 , (c) k_2 , (d) k_3 , (e) k_4 .

Based on the simulations, the optimum slat angles for each scenario and observed zones, the east and west zones, are shown respectively in Table 4. Meanwhile, the annual simulation results in the adaptive shading design option are displayed in Figure 15.

Table 4. Optimum slat angle for the east and west zones in the adaptive shading design option.

Orientation	k_1	k_2	k_3	k_4
East	-10°	-15°	40°	45°
West	-15°	-15°	40°	45°

Figure 15. Annual simulation results in the adaptive shading design option.

Compared to the results in the fixed shading design option (Figure 9), Figure 15 suggests that the sDA_{300/50%} values in all zones are relatively maintained, but the ASE_{1000,250} values are significantly reduced so that all values are now less than the maximum target of 20%. In fact, ASE_{1000,250} values in the east, south, and west zones are even smaller than the earlier LEED criterion of 10%. The ASE_{1000,250} values in the north zone are about 12%, which is likely due to the contribution of direct sunlight in the middle of the year, given that the building is located at a latitude of 6° S.

4. Discussion

4.1. Annual Glare Probability

Throughout this study, glare indices are not directly computed in the simulation. Instead, the ASE_{1000,250} is employed as a proxy of visual discomfort, according to suggestions from the literature [55,56]. To observe the empirical relation, simulation data of ASE_{1000,250} from reference [55] are extracted, for the case of horizontal shading devices in a real office building in Bandung, Indonesia. The data are compared with the corresponding %DGP_{>0.21}, which indicates the annual time fraction in which daylight glare probability (DGP) > 0.21 is achieved, at the nearest observer position to the window. The DGP threshold of 0.21 is chosen based on the suggestion in the literature regarding daylight glare perception in tropical office buildings [60,61].

The predicted maximum values of %DGP_{>0.21} from the reference [55] are shown in Figure 16. While the data are generally scattered, it is observed that they can be divided into two regimes: those with a ‘steep’ gradient (mostly at ASE_{1000,250} < 10%) and those with a less steep gradient (mostly at ASE_{1000,250} > 20%). It is likely that the first regime represents situations dominated with relatively high contrast in the field of view, whereas the second regime represents those with relatively low contrast. The regression model to

predict the maximum $\%DGP_{>0.21}$ from $ASE_{1000,250}$ (x) values in each regime, for the average and 95% upper and lower boundaries, are also provided in Figure 16.

Figure 16. Regression model of the maximum $\%DGP_{>0.21}$ with respect to $ASE_{1000,250}$, based on data from reference [55].

Based on the regression model, the maximum $\%DGP_{>0.21}$ values in this study can be predicted, taking the uncertainties into account. The predicted maximum $\%DGP_{>0.21}$ values for the simulation results in the baseline, fixed shading, and adaptive shading design options are summarised in Table 5. Notice that at high $ASE_{1000,250}$ values ($>20\%$), only the low contrast situation is considered, whereas at low $ASE_{1000,250}$ values, high and low contrast situations are considered. It is clear that the annual glare probability is the highest in the baseline scenario (48–86% in the west zone) and is the lowest in the adaptive shading design scenario (0–6% in the west zone as well), as expected from the $ASE_{1000,250}$ values.

Table 5. Predicted maximum $\%DGP_{>0.21}$ values for the simulation results in the baseline, fixed shading, and adaptive shading design options.

Design Option/Zone	ASE _{1000,250} (%)	Predicted Max. %DGP _{>0.21} (%)			Regime
		95% Lower	Average	95% Upper	
Baseline					
North	39.8	34.2	49.0	63.9	Low contrast
West	61.7	47.9	67.1	86.3	Low contrast
South	21.8	22.9	34.2	45.4	Low contrast
East	55.2	43.8	61.7	79.6	Low contrast
Fixed shading					
North	12.5	17.1	26.5	35.9	High contrast
	12.5	41.9	50.6	59.3	Low contrast
West	38.0	33.1	47.5	62.0	Low contrast
South	3.0	2.8	7.4	12.0	High contrast
	3.0	3.4	7.8	12.1	Low contrast
East	37.9	33.0	47.5	62.0	Low contrast
Adaptive shading					
North	12.1	16.8	26.2	35.5	High contrast
	12.1	40.1	48.6	57.0	Low contrast
West	1.8	0.0	2.0	6.1	High contrast
	1.8	0.0	2.3	6.1	Low contrast
South	3.0	2.8	7.4	12.0	High contrast
	3.0	3.4	7.8	12.1	Low contrast
East	1.9	0.0	2.3	6.4	High contrast
	1.9	0.0	2.6	6.5	Low contrast

4.2. General Discussion

This study focuses on optimising internal, horizontal shading devices on the four façade orientations of a high-rise office building in a tropical city, with respect to the annual daylight metrics, through computational modelling and simulation. A reflective horizontal shading device has been recognized for its good performance in providing uniform and well-distributed daylight illumination in a room [12,37,40,51,57]. As well as this, by focusing on this type of shading device, this study aims to validate the impact of the shading device on the annual daylight inside a building annually and reveal the factors that may affect its performance by doing a step-by-step optimisation to each room. The optimisation is conducted using parametric simulation and the evaluated parameters are based on LEED standard for annual daylight metrics, namely $sDA_{300/50\%}$ and $ASE_{1000,250}$. By using these parameters, the impact of daylight and direct sunlight on the annual daylight performance of the zone can be observed. While not directly calculated in this case, it is also expected that the increase of $ASE_{1000,250}$ will result in an increase of cooling energy demand in the buildings, due to the increasing quantities of direct solar irradiance.

In recent years, simulation has been proven as an important tool that can help designers to make quick and better decisions when designing a building with good performance [6,10,25,37,40,57]. This study also yields similar results, where the simulation framework can be helpful in providing design guidelines for choosing effective shading device systems with optimum daylight performance. Attia et al. [19], in their review on current trends and future challenges of adaptive façade system performance, mentioned that one of the main problems of adaptive façade implementations is the lack of recognition of building level performance while designing such a façade [19]. In this study, the simulation framework aims to help designers in developing appropriate façade systems, focusing not only on the product or component level, but also on the building level.

The simulation in this current study is conducted with three design options on four zones, each representing the cardinal orientations in a high-rise building. The first design option is the baseline scenario, which has been improved with the addition of fixed shading devices in the second design option. The second design option can be further improved with the adaptive shading devices as the third design option. Simulation of these multiple stages suggests that applying the adaptive system in all zones is unnecessary. Instead, a hybrid or combined system between adaptive and fixed facade systems should be sufficient to achieve the optimum annual daylight performance.

The parameters to be optimised on the fixed shading system are the slat numbers and their surface reflectance. However, in the preliminary simulation of the second design option, it is found that the reflectance does not significantly affect $sDA_{300/50\%}$ and practically yields no impact at all on $ASE_{1000,250}$. Thus, to optimise this type of fixed shading system, designers should focus more on the number of slats. Furthermore, the simulation indicates that the south zone may require fewer slats than the other zones. In the second design option, it is found that the installation of fixed shading system is enough for the north and south zones, since the criteria of $sDA_{300/50\%}$ and $ASE_{1000,250}$ have been achieved in these zones. Hammad et al. [12] also suggested similar findings in their study on an actual building in Abu Dhabi, where static horizontal louvres were considered sufficient for the south side and were also preferable in terms of the energy saving potential [12].

However, the third design option is only necessary for the east and west zones because the LEED criteria for $sDA_{300/50\%}$ and $ASE_{1000,250}$ values have not been met in these zones. Additional interventions are required in the form of an adaptive shading system utilising indoor workplane illuminance as the stimulus, while having the slat angle as the adaptive property. It is recommended to identify the relevant properties of the system during the design process, because the implementation of a fully adaptive façade can be costly [12,19]. In other words, by conducting modelling and simulation in the early design phase, architects and building designers will save the installation and operational costs for the systems and focus only on the most critical zones in the building. The associated costs in study are not calculated, as it would not be very precise due to the high uncertainty of

the construction parameters. It is nonetheless an important issue, which can be suggested as a follow-up of this study in the future.

In the green building application, daylighting codes for the Indonesian context are available from the Green Building Council Indonesia (GBCI), which recommends the use of a workplane illuminance threshold of 300 lx at 30% of the space, although the recommended temporal threshold and the sky model are not specifically mentioned [62]. Alternatively, the current Indonesian national standard on daylighting in buildings [63] is also available, but the recommended metric is the sky component based on the outdated uniform overcast sky model, which is unlikely to be applied in practice.

Generally, optimising daylight performance has been one of the well-known techniques in the approach towards having energy-efficient buildings [6–9,12–14]. The optimisation itself can be performed in many ways, such as selecting the appropriate WWR [6,8,10] and/or specific façade systems [10,12,20,25,37,40]. The façade systems can also be modified from fixed [12,20] to adaptive shading devices [12,20,25,37,40]. However, despite the potential, adaptive shading or façade systems still have several challenges and issues to be addressed in practice [19], due to several disadvantages, as follows: (1) adaptive façade systems are not always user friendly, and they do not empower the users through interaction with the facade system and personalized control; (2) it has relatively high investment cost and may increase operational costs; (3) it still lacks a generic and standardized assessment framework, criteria and delivery process; (4) it frequently ends up being tailor made solutions that are time consuming, requiring highly skilled expertise and intensive coordination and collaboration; (5) it often comes up as a complex high-tech system that requires intelligent and flexible automation and predictive control; and (6) it requires a steep learning curve to educate users and facility managers to optimally operate them.

The system implemented in this study should be able to allow the users to take control in certain situations, resulting in a more flexible hybrid-system that can adapt to various conditions. An internal shading device is a logical option to address several disadvantages of adaptive façades, as it is easier to be maintained and to be operated by the building users and facility managers. Moreover, as opposed to internal shading devices, external shading devices tend to limit the potential of the adaptive façade and often only serve an aesthetic purpose, which is also likely to increase the risk of energy use and operational maintenance [19]. In this study, the workplane illuminance range is classified into only four scenarios to consider a more robust system and provide a low-cost adaptive shading system that can still meet the $sDA_{300/50\%}$ and $ASE_{1000,250}$ requirements. Furthermore, the illuminance sensor locations are all located on the workplane, which is relatively easy to monitor, user-friendly, and low-cost. Meanwhile, in the study of Eltaweel et al. [40], an automated louvre was developed with parametrically reflective slats, using the sun movement as the stimulus for automated shading [40,57]. Therefore, the follow-up of this particular topic can be directed towards integrating various types of illuminance or irradiance sensors, so that the optimisation outcomes will be more reliable and applicable in practice.

All of the simulation processes are conducted in *Grasshopper* using additional plug-ins, such as *Honeybee* and *Ladybug*, while the optimisation of the shading devices properties is conducted by iterations from several *Grasshopper* simulations. As the simulation is conducted on the highest floor of the building, it can be assumed that there is little to no impact of the outside context that may cause reflection onto the building. However, in the design practice, the surrounding context may yield significant impact on the building daylight performance. Each design project has different exterior surroundings. Future research will be conducted to seek the impact of the building height and context on the annual daylight metrics in the indoor spaces.

Another possibility of future development of the adaptive shading topics is to create better integration with the electric lighting systems, so that each lamp or luminaire can be adjusted in harmony with the shading devices, to yield a more significant lighting energy saving [6–9,13,14]. There are also possibilities to further develop other shapes or

types of shading devices, such as vertical [12], folding or rotating [25,30], and memory alloys [26]. Such development shall again be started with modelling and simulation in the early design phase. An on-going investigation in the authors' group currently focuses on umbrella-shaped shading devices and their potential for adaptive façade system.

Overall, the main contribution of this study is the proposed optimisation of shading devices in high-rise buildings, considering the daylight admission from the four cardinal orientations in the context of the tropical region.

5. Conclusions

Design optimisation of internal, horizontal shading devices using fixed and adaptive shading design options, involving the width and angle of the slats, has been demonstrated in this study for the case of a high-rise building in the tropics. Four façade orientations are considered simultaneously, corresponding to four sampled zones. The orientation practically influences the $sDA_{300/50\%}$ and $ASE_{1000,250}$ in all zones.

Under the fixed shading design options, the $sDA_{300/50\%}$ and $ASE_{1000,250}$ targets ($\geq 55\%$ and $\leq 20\%$, respectively) can be achieved only on the north and south façades. The adaptive shading design option is thus implemented on the east and west façades, considering four scenarios based on the average workplane illuminance. Simulation results of the adaptive option suggest that all metrics in all zones can now satisfy the performance requirement, with $sDA_{300/50\%} \geq 74\%$ and $ASE_{1000,250} \leq 12\%$. The highest $ASE_{1000,250}$ values are found in the north zone, due to the direct sunlight contribution in the middle of the year.

Overall, this study has contributed to the development of knowledge regarding the optimisation of shading devices in high-rise buildings, considering the daylight admission from the four cardinal orientations, in the context of the tropical region. Based on the findings, in the tropical region, the fixed shading design option can be sufficient on the north and south facades, whereas the adaptive option is recommended on the east and west facades. While the associated construction costs of the proposed design options are not calculated due to the high uncertainty of the construction parameters, it can be suggested as a follow-up study in the future.

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