ENHANCING THE DAYLIGHT AND ENERGY PERFORMANCE OF EXTERNAL SHADING DEVICES IN HIGH-RISE RESIDENTIAL BUILDINGS IN DENSE URBAN TROPICS

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ABSTRACT

This study examines the daylight and energy performance of 27 external shading scenarios in a high-rise residential building in the urban tropics. The cooling energy, daytime lighting energy and the spatial daylight autonomy (sDA) of the building model were simulated in *Rhino3D* and *Grasshopper* simulation software. The best performance scenario (vertical and horizontal shading on the twentieth floor, horizontal shading only for the eleventh floor and no shading for the second floor) satisfied 75 $sDA_{(300lx|50)}$ with corresponding annual enery performance of 16%–20% in the cardinal directions. The baseline scenario, which is the current practice of providing balconies on all floors, reduced daylight to less than 75 sDA on the eleventh and second floor, even though it had higher annual enery performance (19%–24%) than the best performance scenario. Application of the design principles to a case study indicated that 58% of the spaces had over 75 sDA for both Baseline and Best performance scenarios, while an increase in enery performance of 1%–3% was found in the Best performance scenario compared to the Baseline.

KEYWORDS

external shading devices, tropics, urban context, enery performance, daylight

INTRODUCTION

Shading devices, such as long eaves, verandas and window shades block direct solar radiation and prevent rain from entering indoors in traditional low-rise residential buildings in the tropics. Even though intense shading compromised the amount of daylight indoors in the past, a shelter was only required for sleeping, while other activities were conducted outside. Therefore, a lack of daylight in residential interiors was not a predominant issue in traditional residential

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architecture in the tropics. However, the dynamics of housing in the tropics have changed. Most activities are now conducted indoors and therefore require adequate daylight levels indoors. In addition, high-rise residential buildings have replaced most of the low-rise housing and are partners in the economic success of tropical countries, such as Singapore and Hong Kong. In Sri Lanka, high-rise buildings have started to change city skylines. Many high-rise residential buildings are designed with external shading devices such as balconies, overhangs and occasionally vertical fins. As building density increases in the tropics, the impact of the urban context on the performance of external shading devices merits investigation.

Impact of external shading devices on daylight and energy performance of buildings in the tropics

Optimising the building envelope for energy performance has several elements to consider. The building wall and glazing construction is the foremost consideration for minimising solar heat gains in the tropics (Al-tamimi et al., 2011; Lai & Wang, 2011). After optimising the wall design and glazing, further savings can be expected by optimising external shading devices for glazed surfaces. Shading devices minimise solar heat gains by reducing solar radiation incident on the glazed area. In addition to being more effective than internal shading devices, external shading devices minimise obstructing the view, are economical and low maintenance (Cho et al., 2014; G. Kim et al., 2012; J. T. Kim & Kim, 2010; Offiong & Ukpoho, 2004; Valladares-Rendón et al., 2017). A well-designed shading device could provide a good balance between shading, daylighting and visibility (Valladares-Rendón et al., 2017).

The effectiveness of shading devices in most studies are measured in terms of energy performance by lowering internal heat gains (Al-tamimi et al., 2012; Cho et al., 2014; Chua & Chou, 2010; Khin et al., 2016; Wu et al., 2017). However, few studies utilise indoor temperature (Al-tamimi et al., 2011; Arifin & Denan, 2015; Freewan, 2014; Offiong & Ukpoho, 2004) as the dependent environmental variable. Effective design of exterior shading devices could altogether replace the use of expensive, high-performance glass (Cho et al., 2014). The application of external shading on clear glazing is more effective than double glazing (Khin et al., 2016). In developing countries in the tropics, such as Sri Lanka, double glazing has the drawback of being too expensive and creating condensation on the exterior of the glazed surface (Laukkarinen et al., 2018).

External shading devices such as overhangs, vertical panels and egg-crate were the most common strategies investigated in residential buildings (Al-tamimi et al., 2012; Cho et al., 2014; Chua & Chou, 2010; Lai & Wang, 2011; Wong & Li, 2007), while perforated solar screens were investigated in office buildings (Bojic et al., 2002; Chi et al., 2017; Evangelisti et al., 2020; Huang & Zhao, 2017; Lavin & Fiorito, 2017; Sherif et al., 2013). Preference in the application of overhangs, vertical panels and egg-crate over perforated solar screens in residential buildings could be due to simple construction, low maintenance and least view obstruction. Studies find egg-crate perform better in mitigating heat gain followed by overhangs and vertical panels (Al-tamimi et al., 2011; Chua & Chou, 2010; Khin et al., 2016; Lai & Wang, 2011; Shahdan et al., 2018). Recent studies have imvestigated the use of photovoltaic panels to replace horizontal shading devices, which could not only minimise heat gain, but also contribute to energy generation (Akbari Paydar, 2020).

Prioritising shading devices in the east-west directions could result in higher energy performance for cooling (Chua & Chou, 2010; Khin et al., 2016; Offiong & Ukpoho, 2004). Khin et al. (2016) estimated annual cooling energy performance of 3.4% on the west facade; 3.3%

savings on the east facade; and 2.6% savings on the north and south facades for egg-crates. The authors also estimate annual cooling energy performance of 1.4% on east and west facades, and 1.0% on north and south facades for horizontal shading devices. By adopting a 0.3–0.9 m horizontal shading device, a 2.62–10.13% cooling load could be saved in the east-west directions (N. H. Wong & Li, 2007).

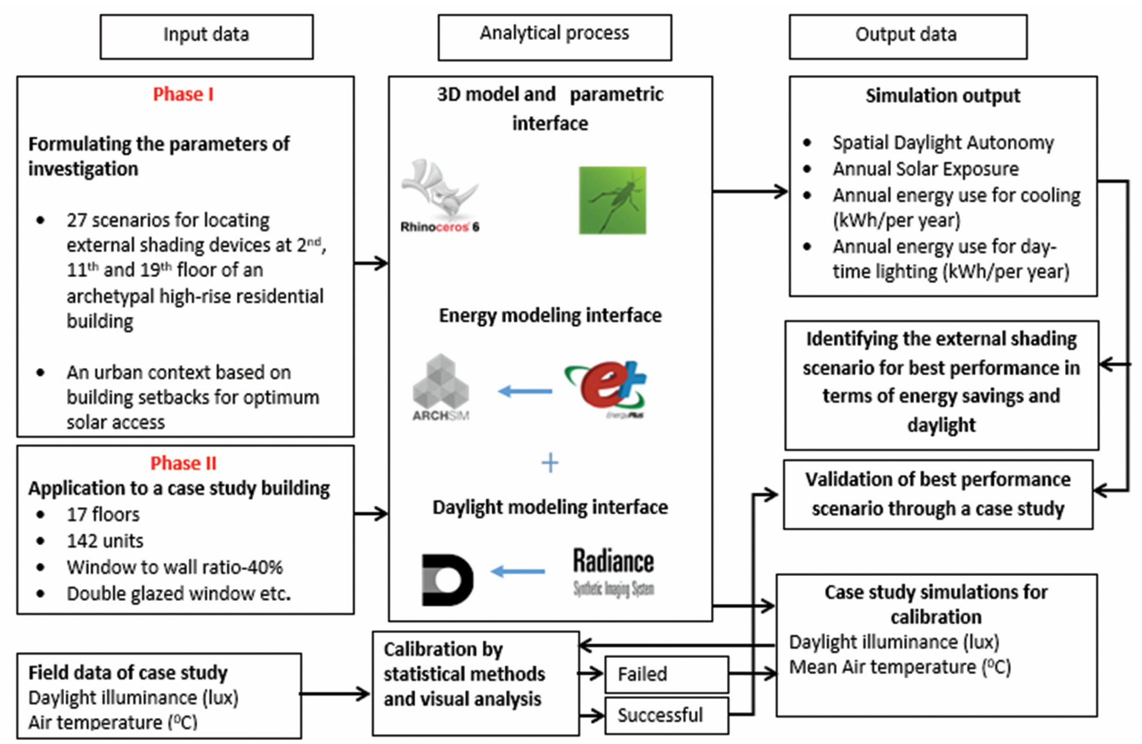
In addition to the benefits of shading devices on minimising heat gain, the negative effects on daylight also need to be considered. However, only a few studies address the daylight and energy performance of egg-crate, overhangs, and fins, which are the most common shading devices in the tropics (Lai & Wang, 2011; Lim et al., 2020; Xie et al., 2017). A study of daylight and cooling energy use in a high-rise residential building in Hong Kong formulated a new index—Energy daylight rate (EDR) for selecting the best scenario of envelope design for both daylighting and shading purposes (Xie et al., 2017). Lim et al. (2020) finds that egg-crate shading was the most proper shading device to block direct sunlight and reduce cooling energy consumption effectively. The effects of several shading devices on heat gains and daylighting in an office building was investigated in Jordan (Freewan, 2014). The study found that egg-crate improved daylight level all day, whereas diagonal fins reduce the illuminance level in the morning, while vertical fins allow for large areas of sun patch to cover an office area in the afternoon. Though multiple horizontal overhangs have better daylighting performance, since they were installed in the vision area of the window, they were expected to have limited applicability due to obstructed view (Cho et al., 2014). The horizontal single overhang and vertical panel, which satisfy both conditions of applicability and sun-shading/daylighting performance, could serve as rational alternatives.

The studies discussed above consider external shading devices in a standalone building. The effects of the urban context were not considered when quantifying the daylight and energy performance of the external shading devices. However, as the effects of contextual shading on building energy use (Han et al., 2017; Lima et al., 2019; Ratti et al., 2015) and daylight (Li et al., 2006; Xue et al., 2014) have been established, a need arises to address the impact of contextual shading on the energy and daylight performance of external shading devices. One of the main negative effects of contextual shading is decreased levels of solar access to the lower floor levels of high-rise residential buildings in the tropics (Jayaweera et al., 2021). In Hong Kong, where very high residential densities exist, low daylighting levels were observed at the lower floors due to neighbouring obstructions resulting in daytime artificial lighting (Xue et al., 2014). In contrast, top floors have better daylight performance while being at risk of overheating (Nebia & Aoul, 2017). The floor level of a high-rise building is an important factor in calculating operational energy use, especially within a dense urban context (Dawodu & Cheshmehzangi, 2017; Li et al., 2006; Nebia & Aoul, 2017; Xue et al., 2014). Architectural interventions of the vertical façade, especially in high-rise buildings, need to respond to the effects of the urban context in order to enhance the energy and daylight performance of the building.

Therefore, the following research objectives were formulated to bridge the research gap identified in the literature review.

- To explore the impact of the urban context on the performance of external shading devices at different floor levels in a high-rise residential building.
- To investigate external shading devices considering dual characteristics (daylight and heat gain) of solar access.

FIGURE 1. Illustration of the methodology.



METHODOLOGY

The study is conducted in two phases as illustrated in Figure 1. The input, analytical and output components in the two phases and their relationship to each other are illustrated in Figure 1.

Phase I—Formulating the parameters of the investigation

High-rise residential buildings are an emerging building typology in Sri Lanka. An archetypal high-rise residential building is characterised following a survey conducted of 22 high rise residential buildings registered under the Condominium Management Authority of Sri Lanka. The characteristics of the archetypal high-rise residential building are tabulated in Table 1. The characteristics are utilised to develop a 3D *AUTOCAD* model of an archetypal high-rise residential building depicting the baseline simulation model (Figure 2).

Formulating the external shading scenarios.

In most high-rise residential buildings in the tropics, the balcony is a typical architectural feature that also acts as a shading device for the glazed area below. The balcony is accessed from the living/dining area or the master bedroom and is continued throughout the facade. In addition to balconies, vertical panels are also utilised in some buildings for shading. Existing research finds that egg-crate, overhangs and vertical panels effectively reduce heat gain in tropics. Twenty-seven scenarios (C1-27) that consist of combined shading (with balcony and vertical panel), horizontal shading (balcony only) and no shading (no balcony or vertical panel) were applied as modifications to the vertical facade in the simulation model. The shading scenarios are given in Table 2. The baseline scenario with three balconies per floor was simulated in C14. The no shading scenario was simulated in C1.

TABLE 1. Characteristics of the archetypal high-rise residential building in tropics.

Building form and facade	
Number of floors	21 floors
Floor height	3m
Plan form	Square central core plan (31 m × 31 m)
Window to wall ratio	36%
Balconies	Two large balconies (7.8 m × 1m × 0.9 m) and one small balcony (4.3 m × 1m × 0.9 m) per floor
Building Materials	
Structure	Concrete structure
Exterior walls	Cement blocks, 200 mm, outside rendered, inside plastered
Window	Single pane 6mm clear glass
Window frame	50 mm extruded aluminium profile
Balcony	Cement blocks, 150 mm, outside and inside rendered
Roof	Reinforced Concrete flat slab, 200 mm, screed 63–12 mm
Floor finish	Tile finish on the concrete slab
Ceiling	Reinforced Concrete slab, 200 mm, screed 63–12 mm painted white
Interior walls	Cement block walls 150 mm, plastered on both sides
Ground	Compacted earth

FIGURE 2. *3D AutoCAD* model of the archetypal high-rise residential building.

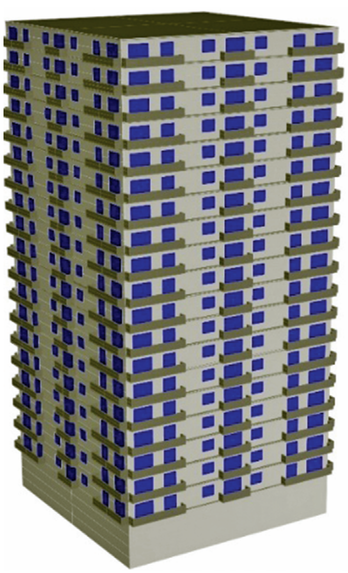


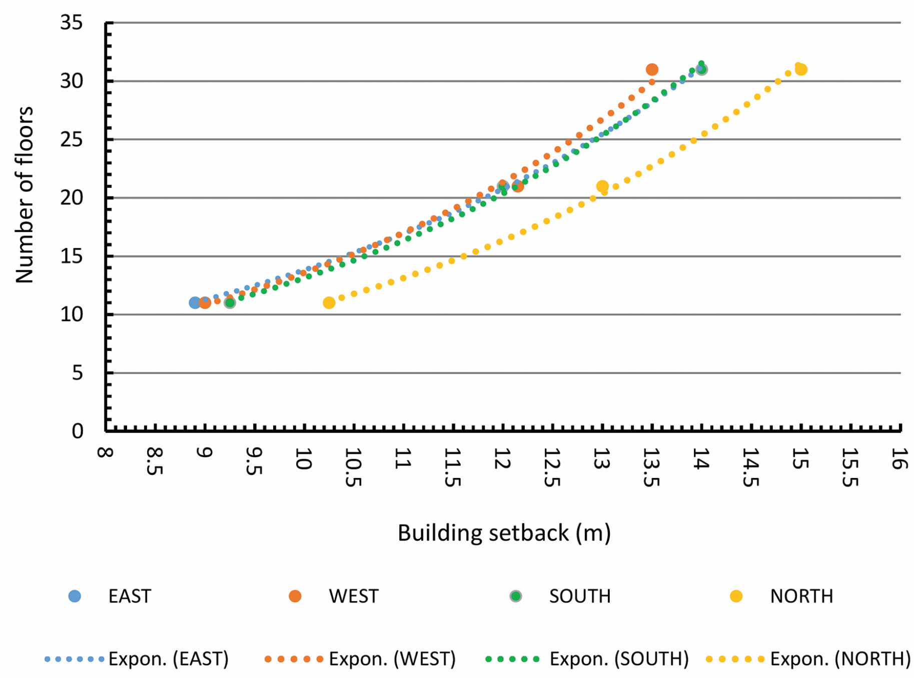
TABLE 2. Modifications to external shading scenarios.

Shading scenario	Floor level		
	19th floor	11th floor	2nd floor
C1	None	None	None
C2	None	None	Horizontal shading
C3	None	None	Combined shading
C4	None	Horizontal shading	None
C5	None	Horizontal shading	Horizontal shading
C6	None	Horizontal shading	Combined shading
C7	None	Combined shading	None
C8	None	Combined shading	Horizontal shading
C9	None	Combined shading	Combined shading
C10	Horizontal shading	None	None
C11	Horizontal shading	None	Horizontal shading
C12	Horizontal shading	None	Combined shading
C13	Horizontal shading	Horizontal shading	None
C14	Horizontal shading	Horizontal shading	Horizontal shading
C15	Horizontal shading	Horizontal shading	Combined shading
C16	Horizontal shading	Combined shading	None
C17	Horizontal shading	Combined shading	Horizontal shading
C18	Horizontal shading	Combined shading	Combined shading
C19	Combined shading	None	None
C20	Combined shading	None	Horizontal shading
C21	Combined shading	None	Combined shading
C22	Combined shading	Horizontal shading	None
C23	Combined shading	Horizontal shading	Horizontal shading
C24	Combined shading	Horizontal shading	Combined shading
C25	Combined shading	Combined shading	None
C26	Combined shading	Combined shading	Horizontal shading
C27	Combined shading	Combined shading	Combined shading

Formulating the urban context

The urban context is modelled at the building setback for optimum solar access given in Figure 3 (Jayaweera et al., 2021). Optimum solar access is defined as a perimeter zone in a high-rise residential building that achieves 75 sDA (300lx|50) with corresponding annual energy performance of 28%–36% in the east-west and 8%–12% savings in the north-south direction (Jayaweera et al., 2021). A hypothetical urban context with an obstruction at 24m in the east and south, 24.3m in west and 26m in the north was modelled for the simulation model (Figure 3).

FIGURE 3. Building setback curves for optimum solar access.



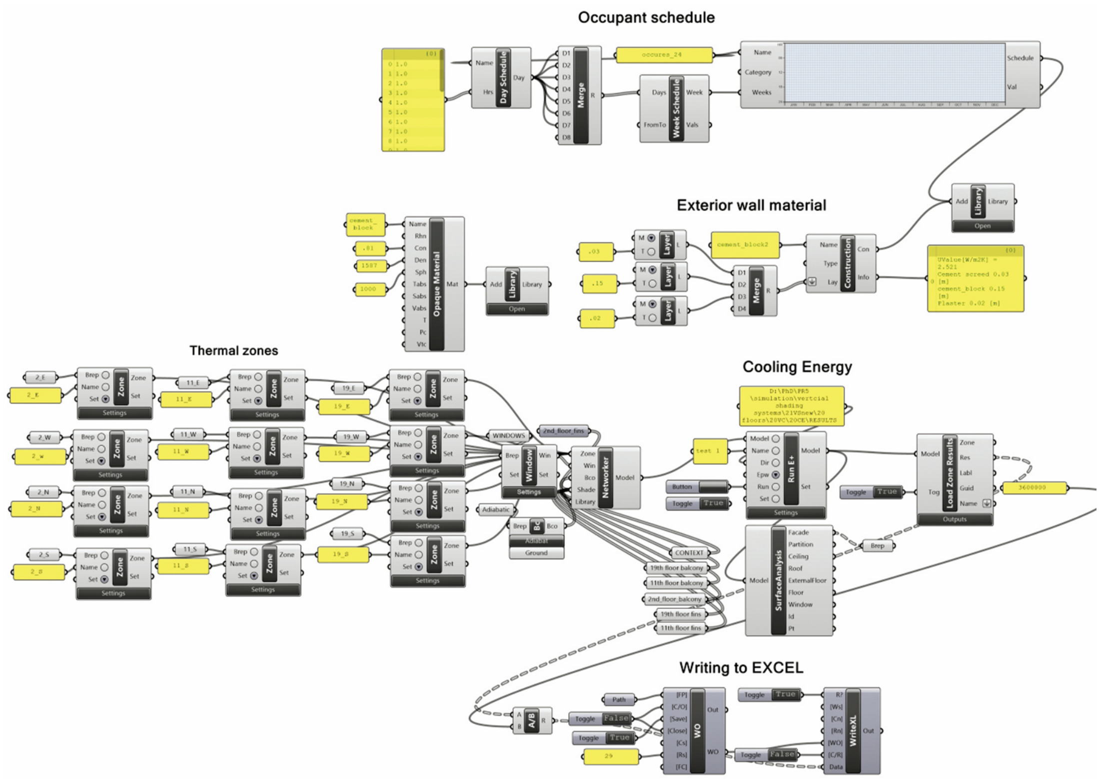
The thermal zone for the simulation model

According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standards, in multifamily buildings, residential units are modelled at least one thermal block per unit except when those units are facing the same orientation, they may be combined into one thermal block. The perimeter thermal zone is modelled at 5 m depth for simulating energy use (ASHRAE/IESNA, 2007). According to the survey, the average depth and width of the typical living room are 6 m x 4.3 m. Due to the average living room depth extending to 6 m in high-rise residential buildings in Sri Lanka, and considering the high levels of solar penetration in the tropics, the depth of the perimeter thermal zone was taken at 6 m and the height at 3 m. Three thermal zones were modelled on the 2nd, 11th and 19th floors.

Considering the requirement of modelling contextual shading, this study utilises *Rhino6 3D* software with an inbuilt *Grasshopper* interface and *Archsim* plugin to simulate energy use. The simulation settings for the thermal zone were selected in order to isolate the effects of solar radiation incident on the vertical exterior wall on the cooling energy use of the thermal zone. Therefore, occupancy, equipment load, lighting, window shading and natural ventilation settings were set to 0. The annual cooling energy (kWh/per year) was calculated for 24-hour operations for 365 days.

The constant setpoint temperature is at 26°C and the cooling limit was set at 100 W/m^2 in the thermal zone. The exterior wall construction is considered to be 200mm cement blocks (U-value of 2.521 W/m^2-K), and glazed facades were modelled as 6 mm clear glass (U-value of 5.84 W/m^2-k). All other surfaces were considered adiabatic. The simulation path for the thermal zone is illustrated in Figure 4.

FIGURE 4. Simulation path for the thermal model.



Daylight and daytime lighting energy model

Spatial Daylight Autonomy (sDA) is calculated as a percentage of floor area that receives at least 300 lux for at least 50% of the annual occupied hours. LEED (Leadership in Energy and Environmental Design) requires a demonstration through annual computer simulations that sDA(300lx|50) is achieved at least 40% (1pts), 55% (2pts), 75% (3pts) of occupied spaces for new construction, core and shell, schools, retail, data centres, warehouses & distribution centres and hospitality (LEED, n.d.). The standard also requires Annual Solar Exposure—ASE$_{(1000\ lx|250)}$ of no more than 10% to be achieved.

In this study, sDA was calculated as a percentage of floor area that receives at least 300 lux for at least 50% of the annual occupied hours. ASE was calculated as 1000 lux for a maximum of 250 hours per year. The use of internal shading devices was not considered in this study. Annual occupied hours were taken as 8.00 a.m. to 5.00 p.m. without daylight saving. Daytime lighting energy was calculated as annual lighting energy (kWh/per year) for the occupied period per simulated floor. The simulation path for the daylight model is given in Figure 4. This study utilises *Rhino6 3D* software with an inbuilt *Grasshopper* interface and *DIVA4* plugin to simulate sDA, ASE and daytime lighting energy. The daylighting grid was generated based on the periphery/core simulation method developed for the thermal zone. The depth of the grid was taken at 6 m. The height of the grid is taken at 0.75 m from the floor level. Grid spacing is taken at 0.6 m. The surface reflectance values of materials are given in Table 3. The four cardinal directions were modelled separately.

Radiance parameters can be set at low, medium, high-quality settings in DIVA4. Higher quality settings could give more accurate results, however, it would take a longer time. Studies

TABLE 3. Surface reflectance values.

Building element	Surface reflectance value
Exterior walls	30 (outside) 70 (inside)
Window	88
Balcony	30
Roof	30
Floor finish	40
Ceiling	80
Interior walls	70
Ground	30

suggest that a five ambient bounce setting is suited to simulating daylight (Dogan & Park, 2017; Moazzeni & Ghiabaklou, 2016). Therefore, a medium quality setting (ab-4, aa-1, ar-256, ad-1024, as-256) was selected for simulating daylight parameters and for considering speed and accuracy.

The energy performance for cooling and day time lighting (CE+LE) as a percentage change was calculated as:

$$\frac{\text{Energy use for CE} + \text{LE}\ (\text{C} = 1 - 27) - \text{Energy use for CE} + \text{LE without external shading devices}}{\text{Energy use for CE} + \text{LE without external shading devices}} \times 100$$

C = energy use for cooling and lighting for external shading scenario

FIGURE 5. Simulation path for the daylight model.

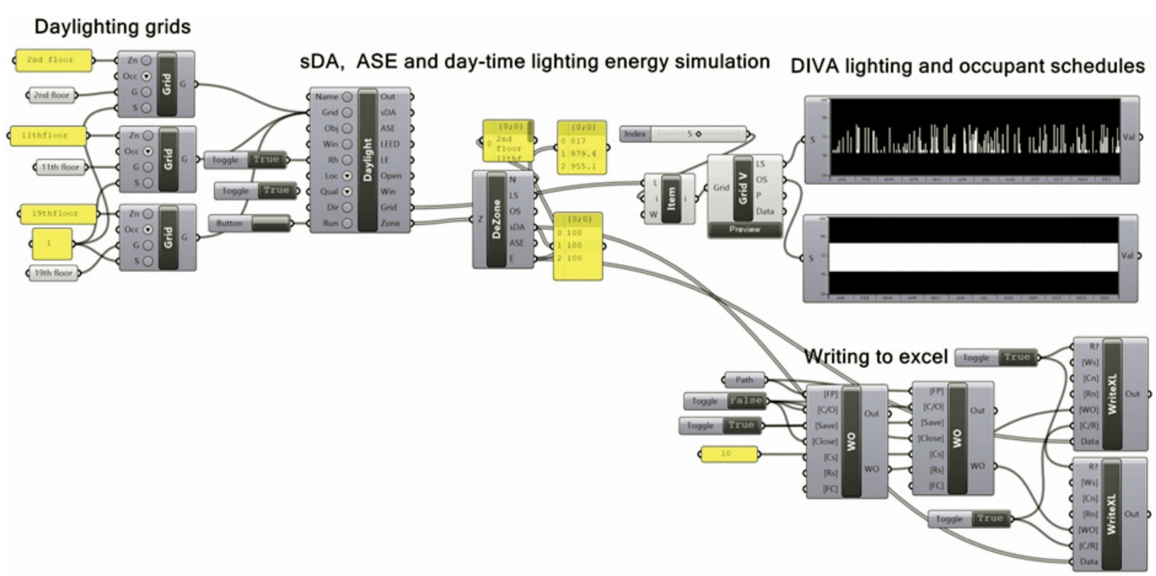
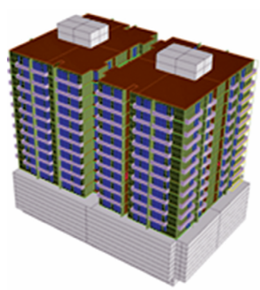
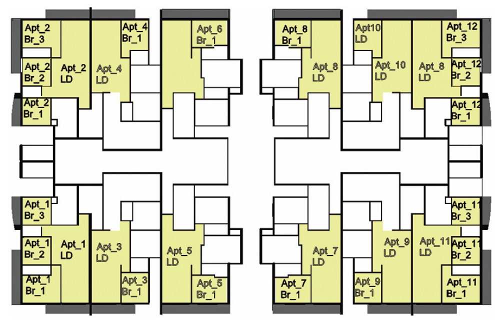
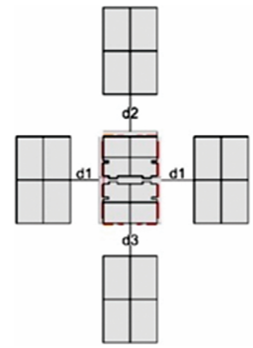


TABLE 4. Characteristics of the case study building.

3D model of the building	Spaces (bedrooms and living rooms) modeled for sDA, LE and CE in a typical floor	Hypothetical urban context
		 d1-22 m, d2-24.4 m d3-22.2 m

Building materials			
Building element	**Material**	**Surface reflectance value**	**U value (W/m^2-k)**
Structure	Concrete structure	30	2.521
Exterior walls	Cement blocks, 200 mm, outside rendered, inside plastered	30 (outside) 70 (inside)	2.521
Window	Double pane 6mm clear glass	88	5.84
Balcony	Concrete and 150mm cement blocks	30	—
Roof	Reinforced Concrete flat slab, 200 mm, screed 63–12 mm	30	Adiabatic
Floor finish	Tile finish on concrete slab	40	Adiabatic
Ceiling	Reinforced Concrete slab, 200 mm, screed 63–12 mm painted white	70	—
Interior walls	Cement block walls 150 mm, plastered on both sides	70	Adiabatic
Ground	Compacted earth	30	—

Phase II-Application of design principles to a case study

The aim of applying the research findings to a case study is to consider design options for a real-world building in a dense urban context. A high-rise residential building with 17 floors and 142 residential units located in the Colombo, Sri Lanka, metropolitan area was selected as the case study (Table 4). However, a limitation of the case study is that high-rise residential buildings are scattered in dense low-rise neighbourhoods in Colombo. Therefore, a hypothetical urban context was developed to simulate contextual shading on the building for the case study. The urban context was developed utilising the building setback curves developed for optimum solar access in Figure 3.

The spaces modelled for daylight and energy use were bedrooms (BR) and living/dining areas (LD) in the residential units (Apt) that have direct solar access from the facade indicated in the typical floor plan in Table 4. The spaces with solar access from multiple cardinal directions and from an air well were not considered for simulation in the case study. As floors up to level 6 were used as car parks, the bottom floors could not be utilised for this study.

Two models, the Baseline case study model (balconies only from the 6th to the 15th floor) and the Best performance scenario model (balconies only from the 7th to the 11th floor and fins and balconies from the 12th to the 15th floor) were simulated for daylight and energy performance (Figures 6 and 7).

RESULTS AND DISCUSSION

Daylight Analysis

Figures 8–10 compare the sDA at different floors of the archetype high-rise residential building simulation model for each cardinal direction. sDA vary 60%–100% for each shading scenario. On the second floor, the highest sDA was observed in the north-south, while on the 19th floor, the highest sDA was observed in the east-west direction. This indicates that contextual shading decreases sDA in the east-west direction compared to the north-south for lower floors. Therefore, the application of external shading scenarios to the east-west façade could result in lower sDA than north-south facades when considering contextual shading effects.

FIGURE 6. Baseline model.

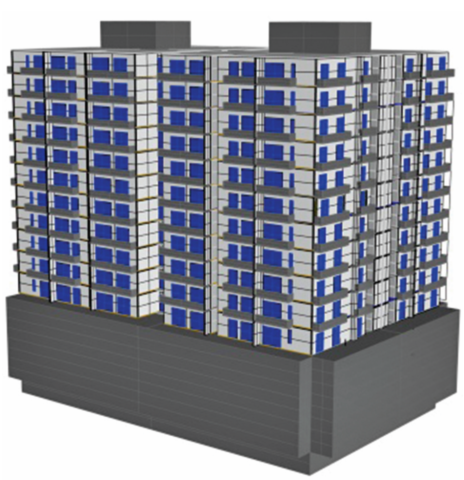


FIGURE 7. Best performance scenario model.

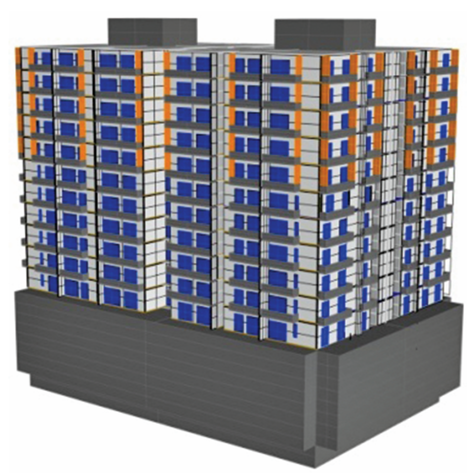


FIGURE 8. Comparison of sDA of different shading scenarios in the 2nd floor.

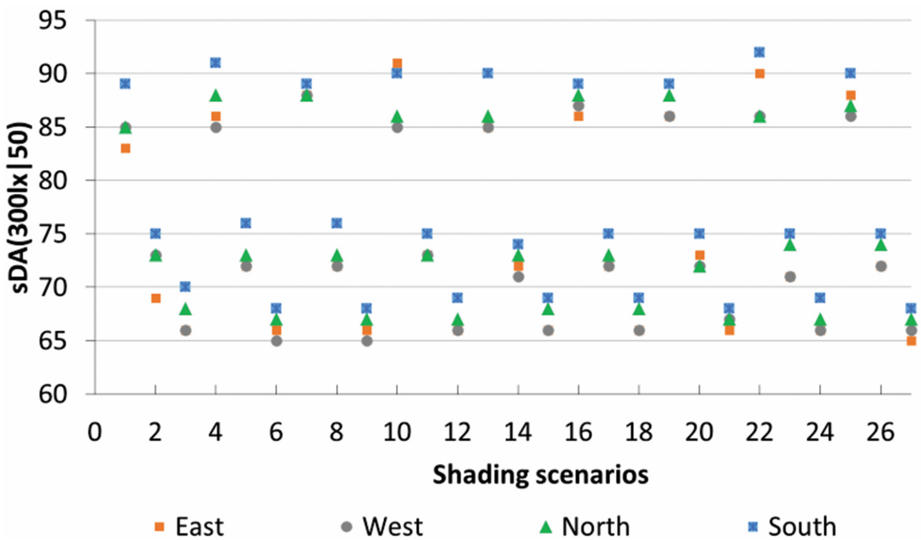
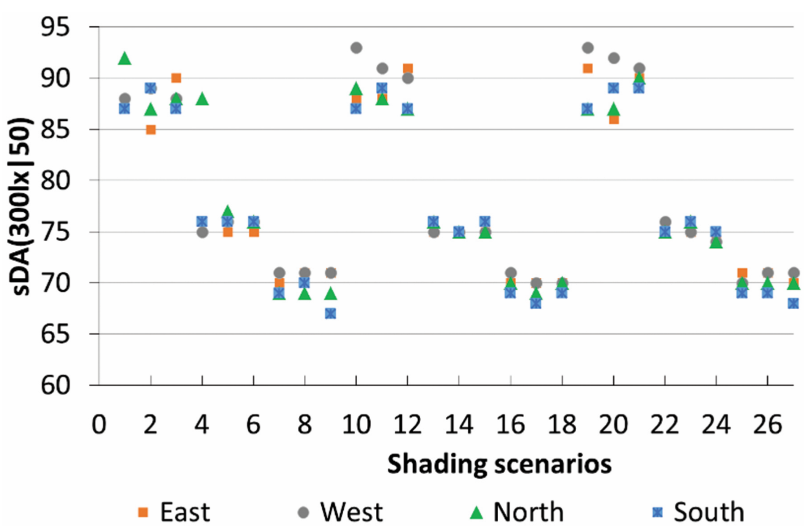


FIGURE 9. Comparison of sDA of different shading scenarios in the 11th floor.



To identify the best performance shading scenario, threshold values for sDA and energy performance need to be established. According to the optimum solar access definition for urban tropics, 75 $sDA_{(300lx|50)}$ is required for the perimeter zone in a high-rise residential building for optimising solar access. Therefore, 75% was taken as the threshold $sDA_{(300lx|50)}$ to be satisfied by all floor levels in the external shading scenario.

Annual solar exposure (ASE) levels corresponding to shading scenarios are given in Table 5. In C22, which is considered the best performance scenario, the ASE ranges from 16% to 30% in the east, 6% to 19% in the west, 1% to 2% in the north and 6% to 17% in the south. High ASE levels in the east are experienced for a few hours in the morning in the tropics. High levels of direct solar exposure for short periods, especially in the morning, is welcome, given the

FIGURE 10. Comparison of sDA of shading scenarios in the 19th floor.

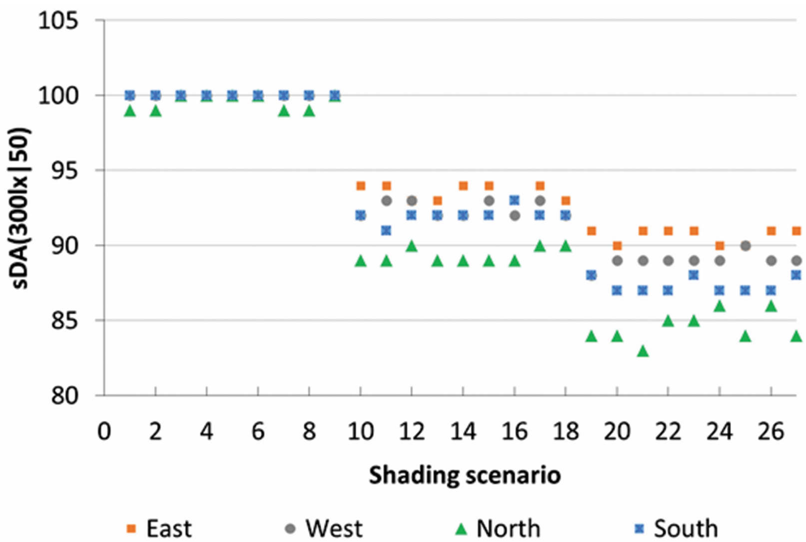


TABLE 5. ASE levels for external shading scenarios.

Scenario	East			North			South			West		
	2_FL	11_FL	19_FL	2_FL	11_FL	19_FL	2_FL	11_FL	19_FL	2_FL	11_FL	19_FL
C1	14.2	14.8	32.4	7.6	7.6	7.6	17.6	17.9	17.9	10.4	10.7	21.4
C2	11	14.8	32.4	2.7	7.6	7.6	7.8	17.9	17.9	6.3	10.7	21.4
C3	13	16.5	32.4	1.8	7.6	7.6	6.2	17.9	17.9	6.3	10.7	21.4
C4	16	13.5	32.4	1.8	7.6	7.6	17.6	8	17.9	10.4	6.7	21.4
C5	13	13.5	32.4	2.7	2.7	7.6	7.8	8	17.9	6.3	6.7	21.4
C6	13	13.5	32.4	1.8	2.7	7.6	6.2	8	17.9	6.3	6.7	21.4
C7	16	13.5	32.4	7.6	1.8	7.6	17.6	6.4	17.9	10.4	6.7	21.4
C8	13	13.5	32.4	2.7	1.8	7.6	7.8	6.4	17.9	6.3	6.7	21.4
C9	13	13.5	32.4	1.8	1.8	7.6	6.2	6.4	17.9	6.3	6.7	21.4
C10	16	16.5	30.8	7.6	7.6	2.7	17.6	17.9	8	10.4	10.7	19.4
C11	13	16.5	30.8	2.7	7.6	2.7	7.8	17.9	8	6.3	10.7	19.4
C12	13	16.5	30.8	1.8	7.6	2.7	6.2	17.9	8	6.3	10.7	19.4
C13	16	13.5	30.8	7.6	2.7	2.7	17.6	8	8	10.4	6.7	19.4
C14	13	13.5	30.8	2.7	2.7	2.7	7.8	8	8	6.3	6.7	19.4
C15	13	13.5	30.8	1.8	2.7	2.7	6.2	8	8	6.3	6.7	19.4
C16	16	13.5	30.8	7.6	1.8	2.7	17.6	6.4	8	10.4	6.7	19.4
C17	13	13.5	30.8	2.7	1.8	2.7	7.8	6.4	8	6.3	6.7	19.4
C18	13	13.5	30.8	1.8	1.8	2.7	6.2	6.4	8	6.3	6.7	19.4
C19	16	16.5	30.8	7.6	7.6	1.8	17.6	17.9	6.4	10.4	10.7	19.4
C20	16	16.5	30.8	2.7	7.6	1.8	7.8	17.9	6.4	6.3	10.7	19.4
C21	13	16.5	30.8	1.8	7.6	1.8	6.2	17.9	6.4	6.3	10.7	19.4
C22	16	13.5	30.8	7.6	2.7	1.8	17.6	8	6.4	10.4	6.7	19.4
C23	13	13.5	30.8	2.7	2.7	1.8	7.8	8	6.4	6.3	6.7	19.4
C24	13	13.5	30.8	1.8	2.7	1.8	6.2	8	6.4	6.3	6.7	19.4
C25	16	13.5	30.8	7.6	1.8	1.8	17.6	6.4	6.4	10.4	6.7	19.4
C26	13	13.5	30.8	2.7	1.8	1.8	7.8	6.4	6.4	7.8	6.4	6.4
C27	13	13.5	30.8	1.8	1.8	1.8	6.2	6.4	6.4	6.2	6.4	6.4
		ASE>10%										

health benefits. In addition, internal shading could avoid unwanted direct solar exposure for short periods (Dogan and Park, 2017). Therefore, high ASE was not considered a disadvantage for residential buildings.

Energy performance analysis

Figure 11 depicts the energy performance of the shading scenarios for the cardinal directions. According to the figure, the highest energy performance from external shading devices were observed in the south, followed by north, west and east. The literature review stated that energy performance from external shading were higher in the east-west directions. However, Figure 11 shows that when considering an urban context and daytime lighting energy use, the north-south direction led to higher energy performance. The maximum energy performance were observed at 25% for C27 for the façade facing south. However, to satisfy the sDA requirement, a lower value of 15% energy performance was selected as the threshold for identifying the best performance scenario.

Discussion on identifying the best performance external shading scenario

The shading scenarios, which satisfied 75 sDA for all three floors simulated in the model and satisfied the 15% annual energy performance threshold, were considered to meet the best performance criteria for this study. Table 6 compares the energy performance for cooling and daytime lighting against the sDA of the simulation model. sDA above 75% are indicated in red, while the annual energy performance above 15% are green. To select the best performance scenario, the minimum threshold set for energy performance and daylight should be satisfied. In the façade facing an obstruction in the east, two scenarios, C13 and C22, satisfy the threshold values for sDA and energy performance. However, C22 has a higher energy performance percentage of 17. The baseline scenario (C14) has higher energy performance; however, it does not meet 75 sDA at the lowest floor level. The results indicate that considering the effects of the west-facing facade, C22 again satisfies both the sDA requirement for all floors and energy performance at 15%. In the north-facing façade, too, only C22 meets both criteria. Therefore, C22 is considered the best performance external shading scenario for all cardinal directions.

FIGURE 11. Comparison of enery performance of shading scenarios for cardinal directions.

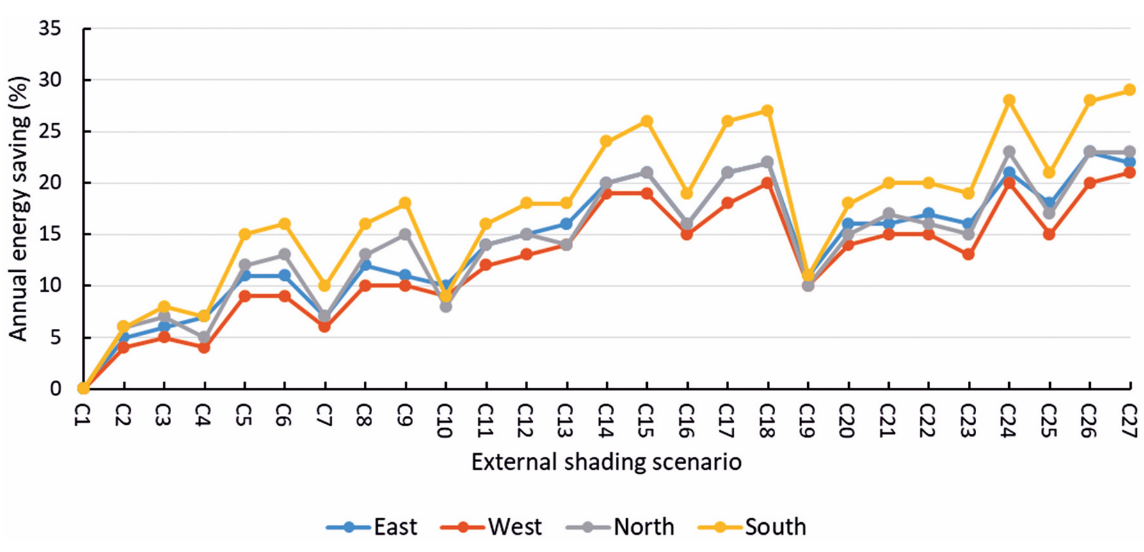


TABLE 6. sDA and enery performance for facades facing east, west, north and south.

Façade facing obstrcution in the east

Scenario	Annual energy savings	sDA (300lx|50) percetnage per floor		
		2_FL	11_FL	19_FL
C1	0	83	87	100
C2	5	69	85	100
C3	6	66	90	100
C4	7	86	76	100
C5	11	72	75	100
C6	11	66	75	100
C7	7	88	70	100
C8	12	72	71	100
C9	11	66	71	100
C10	10	91	88	94
C11	14	73	88	94
C12	15	66	91	93
C13	16	85	75	93
C14	20	72	75	94
C15	21	66	75	94
C16	16	86	70	93
C17	21	72	70	94
C18	22	66	70	93
C19	11	86	91	91
C20	16	73	86	90
C21	16	66	90	91
C22	17	90	75	91
C23	16	71	75	91
C24	21	66	74	90
C25	18	88	71	90
C26	23	72	71	91
C27	22	65	70	91

Façade facing obstrcution in the West

Scenario	Annual energy savings	sDA (300lx|50) percetnage per floor		
		2_FL	11_FL	19_FL
C1	0	85	88	100
C2	4	73	89	100
C3	5	66	88	100
C4	4	85	75	100
C5	9	72	76	100
C6	9	65	76	100
C7	6	88	71	100
C8	10	72	71	100
C9	10	65	71	100
C10	9	85	93	92
C11	12	73	91	93
C12	13	66	90	93
C13	14	85	75	92
C14	19	71	75	92
C15	19	66	75	93
C16	15	87	71	92
C17	18	72	70	93
C18	20	66	70	92
C19	10	86	93	88
C20	14	72	92	89
C21	15	67	91	89
C22	15	86	76	89
C23	13	71	75	89
C24	20	66	74	89
C25	15	86	70	90
C26	20	72	71	89
C27	21	66	71	89

Façade facing obstrcution in the North

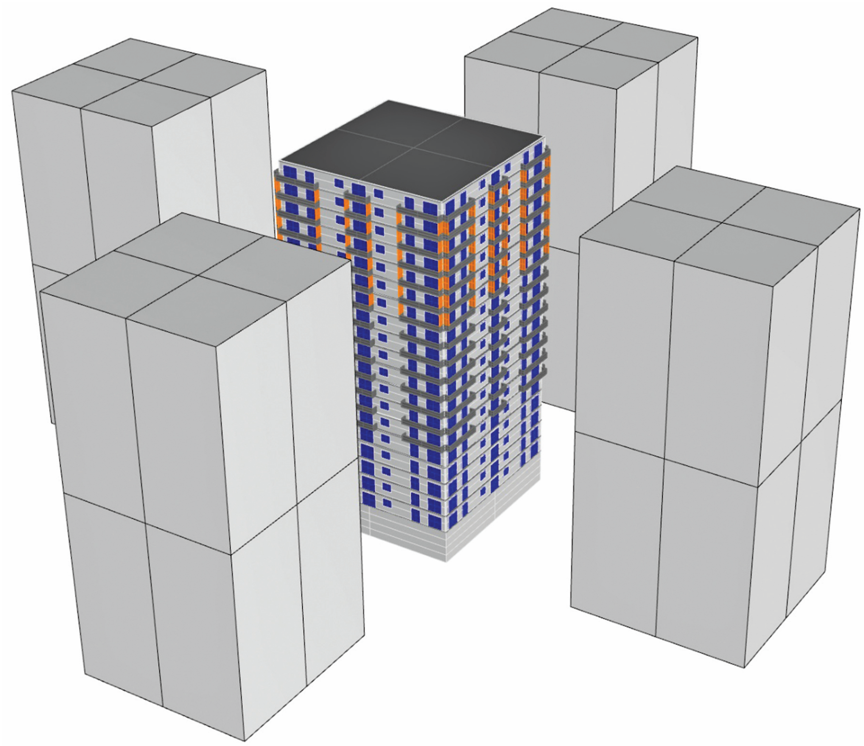
Scenario	Annual energy savings	sDA (300lx|50) percetnage per floor		
		2_FL	11_FL	19_FL
C1	0	85	92	99
C2	6	73	87	99
C3	7	68	88	100
C4	5	68	88	100
C5	12	73	77	100
C6	13	67	76	100
C7	7	88	69	99
C8	13	73	69	99
C9	15	67	69	100
C10	8	86	89	89
C11	14	73	88	89
C12	15	67	87	90
C13	14	93	76	89
C14	20	73	75	89
C15	21	68	75	89
C16	16	88	70	89
C17	21	73	69	90
C18	22	68	70	90
C19	10	88	87	84
C20	15	72	87	84
C21	17	67	90	83
C22	16	86	75	85
C23	15	74	76	85
C24	23	67	74	86
C25	17	87	70	84
C26	23	74	70	86
C27	23	67	70	84

Façade facing obstrcution in the South

Scenario	Annual energy savings	sDA (300lx|50) percetnage per floor		
		2_FL	11_FL	19_FL
C1	0	89	87	100
C2	6	75	89	100
C3	8	70	87	100
C4	7	91	76	100
C5	15	76	76	100
C6	16	68	76	100
C7	10	89	69	100
C8	16	76	70	100
C9	18	68	67	100
C10	9	90	87	92
C11	16	75	89	91
C12	18	69	87	92
C13	18	92	76	92
C14	24	74	75	92
C15	26	69	76	92
C16	19	89	69	93
C17	26	75	68	92
C18	27	69	69	92
C19	11	89	87	88
C20	18	75	89	87
C21	20	68	89	87
C22	20	92	75	87
C23	19	75	76	88
C24	28	69	75	87
C25	21	90	69	87
C26	28	75	69	87
C27	29	68	68	88

(pink)	> 75% sDA(300lxl50)	(green)	> 15% annual energy savings

FIGURE 12. The best performance scenario (C22) of external shading for a dense urban context.



The above analysis establishes that architectural interventions at the building façade need to be modified at different floor levels to enhance daylight and energy performance. The best performance external shading scenario was identified in the study as Scenario 22, where the 19th floor had combined shading, the median floor had only balconies, and the 2nd floor had no shading devices. The following design principles based on the best performance scenario were formed from the analysis. The design principles are applied to SM2 and illustrated in Figure 12.

- When considering the entire façade, the windows in the bottom one-third of the building's floors should be without or have minimal shading techniques.
- The windows in the middle one-third of the building should have only horizontal shading (e.g., balconies).
- The top one third should have combined fins and balconies for the external shading of windows.

CASE STUDY ANALYSIS

Calibration of the simulation model of the case study

Indoor air temperature measurements and daylight illuminance levels were collected using three Hobo data loggers (MX-2202) in a bedroom. During data collection, the windows and doors were closed with curtains open at all times, and there was no occupation. Data was collected from 15.06.2020 to 23.06.2020 at 10-minute intervals. Since the bedrooms were in use, the data collection period was limited to eight days.

For the calibration of the case study, the Coefficient of Variation of Root Mean Square Error—CV (RMSE) and Normalised Mean Bias Error (NMBE) shall be determined by comparing simulated data ($\hat{s}$) to the field data (m_i), with p = 1. ASHRAE guideline 14 dictates that simulation models are to be calibrated within CV ($RMSE_{hourly}$) value of 30% and $NMBE_{hourly}$ 10% (Ruiz & Bandera, 2017).

$$CV\left(RMSE_{hourly}\right) = \frac{\sqrt{\frac{\sum\left(m_i - \hat{s}_i\right)^2}{(n-p)}}}{\bar{m}} \times 100$$

Equation 2: Coefficient of variation of root mean square error (%)

$$NMBE_{hourly} = \frac{\sum\left(m_i - \hat{s}_i\right)^2}{\bar{m}(n-p)} \times 100$$

Equation 3: Normalised mean bias error (%)

The thermal model was simulated without occupation and natural ventilation to match indoor conditions during field data collection. The mean air temperature of the 3 data loggers was used to calibrate the simulation model. The thermal model was calibrated within the ASHRAE 14 guidelines, as seen in Table 7. The same points corresponding to the field data were simulated for hourly illuminance using the *DIVA4* plugin. However, due to high direct solar radiation levels, the data loggers closest to the window recorded spikes in illuminance. Therefore, only the data logger located furthest away from the window was used for the calibration. According to Table 11, daylight illuminance was within the stipulated NMBE threshold; however, the CV ($RMSE_{hourly}$) threshold was not met. Therefore, to further investigate the issues in daylight calibration, the field and simulated data were compared in a graph. According to the graph, lower field illuminance levels overlap with simulated data. The errors in simulated data were mostly observed at the highest values during mid-day due to direct solar radiation. As the errors were mainly due to direct solar radiation and not due to errors in calculating diffused solar radiation, the daylight simulation model could be used for estimating sDA, ASE and daytime lighting in this study.

TABLE 7. Measures of uncertainty in air temperature and daylight illuminance levels in the case study.

	Standard deviation in field data	$NMBE_{hourly}$	CV ($RMSE_{hourly}$)
Air temperature	0.28	1.8%	2.8%
Day light	117.15	6%	46%

Discussion on daylight and energy performance of the case study

Tables 8 and 9 demonstrate the sDA and energy performance of the baseline and the best performance scenario model. The baseline and best performance scenarios both satisfied 62% of the spaces simulated with sDA of 55%, while 58% spaces meet 75% sDA. An increase in sDA is observed at higher floor levels due to the lower contextual shading fraction at the higher floors in both scenarios. sDA is below 55% for all the living rooms compared to the bedrooms, where 93% of bedrooms have above 55% sDA. Lack of daylight in living rooms could be attributed to the increase in room depth of living rooms. Energy performance were higher for the lower floors than the higher floors for both scenarios. Combined shading from the 12th to 16th floors (best performance scenario) increased energy performances for an average floor by 1.7% in the east, 2% in the west, 6% in the north and 7% compared to the baseline scenario for the respective floors.

Table 10 summarises the simulated results. The sDA percentage does not change for the baseline and best performance scenario. As the bottom floors were car parks, the benefits of the non-shading for lower floors on increasing daylight levels could not be investigated in this case study. The benefits of having combined shading for energy performance in the top floors

TABLE 8. Annual energy performance and sDA for the Baseline scenario.

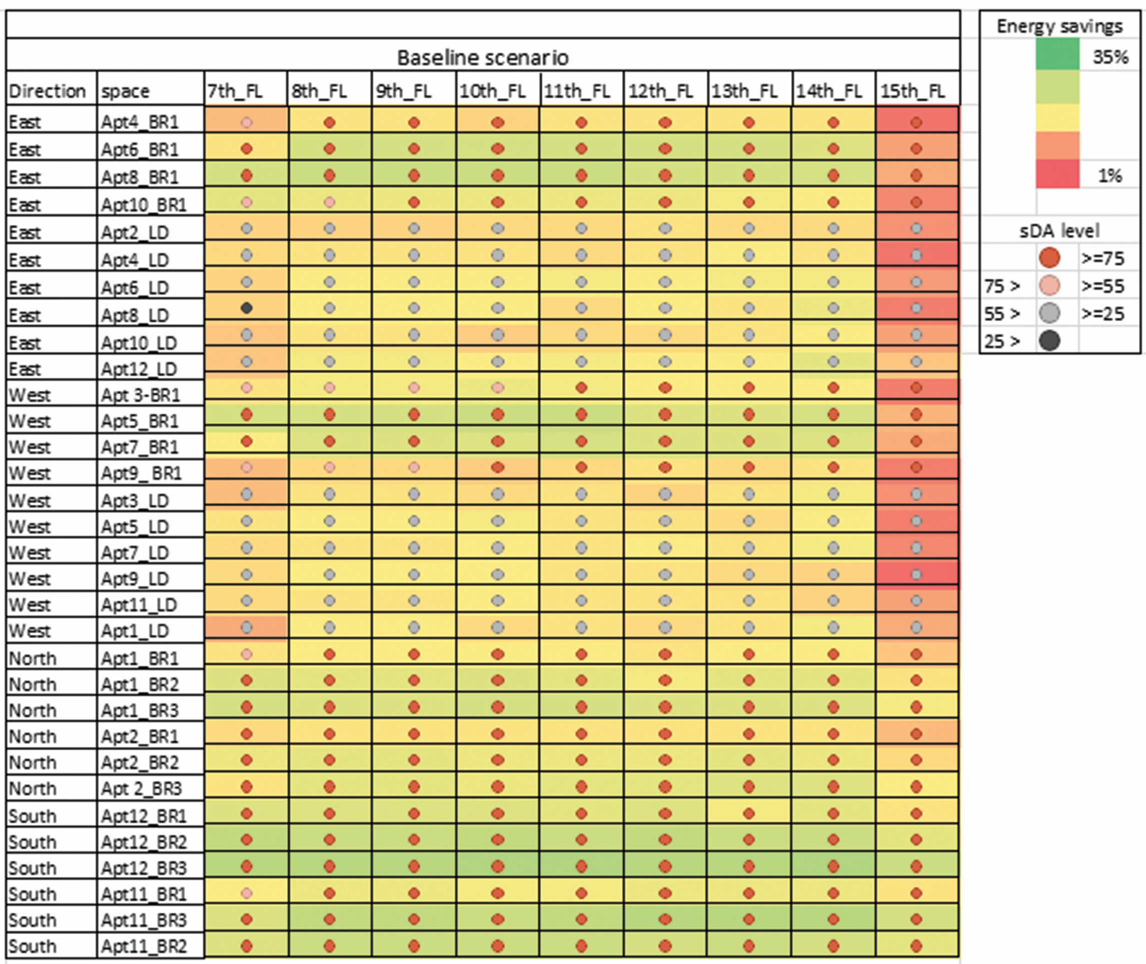


TABLE 9. Annual enery performance and sDA for the Best performance scenario.

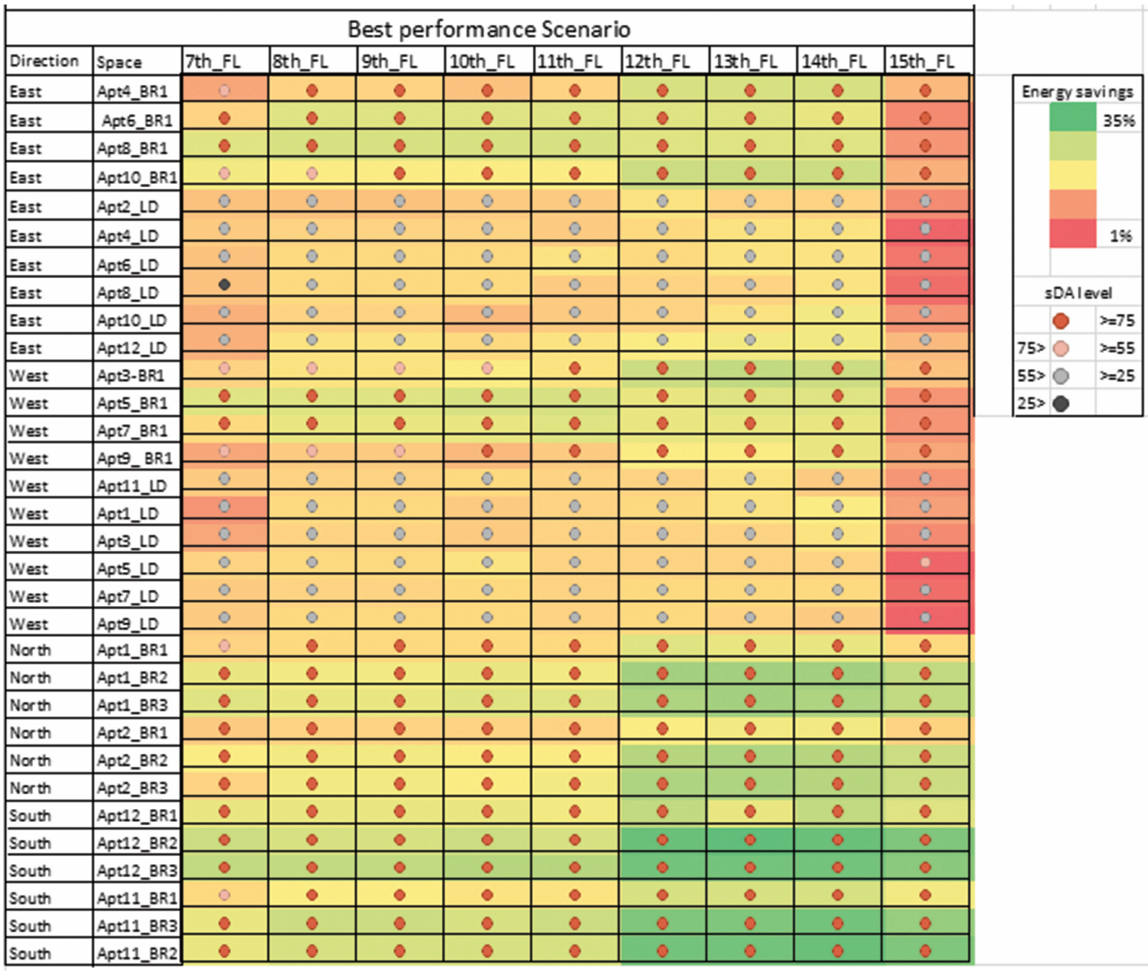


TABLE 10. Comparison of $sDA_{(300lx|50)}$ and enery performance of the case study.

	Percentage of spaces with:		Average annual enery performance percentage			
	sDA >=55	sDA >=75	East facade	West facade	North facade	South facade
Baseline scenario	62	58	16.1	15.7	18.3	22.0
Best performance scenario	62	58	17	16.5	21.2	25.1

were observed in this study, even though the effects were marginal. A 1% energy performance could be observed in the east-west and 3% in the north-south direction. The marginal increase in energy performance percentage could be because the case study building had structural elements (ducts, structural walls, columns) that act like fins that provide shading to the glazed area, included in the baseline scenario.

CONCLUSION

External shading devices are architectural features controlling solar access to high-rise residential buildings in the tropics. However, as tropical cities are becoming more dense, the effectiveness of external shading devices in terms of energy performance and daylight need to be considered within the urban context. This study proposes modifications to the external shading devices at different floor levels to enhance the daylight and energy performance of high-rise residential buildings in the tropics.

An archetype high-rise residential building of 21 floors was developed to simulate the impact of the urban context on external shading scenarios. Twenty-seven shading scenarios (C1-27) consisting of combined shading (with balcony and vertical panel), horizontal shading (balcony only) and no shading (without balcony or vertical panel) were modelled for the 2nd, 11th and 19th floor. The urban context was developed based on the building setback curves developed for optimum solar access for each cardinal direction. Using 3D modelling software *Rhino6*, parametric interface *Grasshopper* and plugins, *DIVA4* and *Archsim*, the performance of the external shading scenarios in terms of daylight and energy performance were simulated.

The literature review stated that energy performance from external shading are higher in the east-west direction. However, when considering urban context and daytime lighting energy use, north-south directions lead to higher energy performance than east-west directions. Shading scenarios that meet 75 sDA for all three floors simulated in the model and satisfy the 15% annual energy performance were considered the best performance external shading criteria for this study. The shading scenario C22 (no shading on the 2nd floor, balcony on the 11th floor, combined shading on the 19th floor) satisfied the sDA requirement on all floors with energy performance of 16%–21%. Therefore, C22 is considered the best performance external shading scenario.

A high-rise residential building with 17 floors and 142 residential units located in Colombo, Sri Lanka, metropolitan area was utilised as a calibrated case study to apply the research findings. The hypothetical urban context was developed using the building setback curves developed for optimum solar access. Two models, the baseline model (balconies only from the 6th to 15th floor) and best performance scenario model (balconies only from 7th to 11th floors and fins and balconies from 12th to 15th floors) were simulated for daylight and energy performance. Because floors up to level 6 were used as car parks, the bottom floors could not be utilised for this study. The baseline and best performance scenario models provide 62% of spaces with an sDA of 55%, while 58% of spaces satisfy sDA of 75%. The benefits of having combined shading for energy performance at the top floors were observed in this study, even though the effects were marginal. An additional 1% energy performance could be observed in the east-west and 3% in the north-south direction in the Best performance model compared to the Baseline model. The marginal energy performance could be because the case study building had structural elements (ducts, structural walls, columns) that act like fins providing shading to the glazed area, included in the baseline model.

LIMITATIONS OF THE STUDY

The scope of research in this study is limited by the building typology and the urban context. The building typology focused here is high-rise residential buildings. The urban tropics are a relatively new context in the study of the implications of increasing densities on solar access. Therefore, this research study is limited to the study of external shading devices in high-rise residential buildings in the urban tropical climate.

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