

Thermal Impact Investigation of Shaded Opaque Walls in Bangkok

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Abstract

The effectiveness of overhang shading devices in mitigating solar radiation on opaque walls is crucial for passive building design in tropical regions. However, opaque walls commonly are side-lined in shading design due to a preoccupation with insulation properties, appearance, and aesthetics. Unprotected walls exposed to solar radiation maximize heat gain, while shaded walls decrease external heat gain and indoor temperature, resulting in improved indoor thermal comfort and well-being. This research employs EnergyPlus and SPSS to investigate the optimal design of overhang shading devices for opaque walls in Bangkok, Thailand. The investigation is divided into two phases: (1) determination of the optimal depth-to-space ratio of overhang devices based on a parametric study of 12 overhang configurations; (2) an evaluation of the ratio in reducing solar radiation. The findings demonstrate a relationship between the device depths and the wall solar radiation and indoor temperature. The optimum depth-to-space ratio is suggested as 1:1.15, which can lower the annual average indoor temperature by 3.53% (1.18°C) compared to the benchmark design. Deeper shading device depths than the optimum depth-to-space ratio can be applied, with a slight improvement in protective performance (and commensurately increased costs). This research underscores the importance of overhang shading devices as a performance-improving strategy for buildings in the tropical climate of Thailand.

Keywords

Passive design, Shading devices, Tropical architecture, Energy conservation

1. Introduction

Architecture is constructed to shelter humans from the elements and to enhance comfort, well-being, and quality of life. Climate is the most fundamental of factors shaping vernacular architecture, which naturally considers the climatic context in conjunction with natural resource availability, human skills, and socio-economic constraints. These prerequisite conditions determine different architectural characteristics that can be discerned worldwide. Climatic adaptation is implanted in vernacular buildings to allow humans and nature to live in harmony. Passive design is one of the most fundamental techniques for architecture to allow humans to adapt themselves to their climatic environment and lower excessive energy consumption.

In hot regions such as the tropics, heat control is a crucially challenging issue relating to energy consumption and sustainability. Heat prevention strategies for exterior surfaces can be incorporated into buildings in the early design stage. Research often investigates the performance of passive design strategies such as building geometries and layouts to marginally decrease total energy consumption (Ferdous & Gorgolewski, 2014; Hatem & Karram, 2020; Parasonis et al., 2012; Srithongchai, 2021; Zhang et al., 2017). However, integrating individual, standalone techniques for low-energy consumption solutions seems insufficient to entirely mitigate the existing hot climate challenge and produce realistic environments promising user comfort. The incorporation of various combinations of energy-saving techniques can achieve better results for indoor thermal comfort and energy savings in various use scenarios. Therefore, each passive design technique should be continuously developed to optimize performance in the target context.

Shading devices have been used in tropical regions since ancient times and they remain an essential architectural element widely used in modern architecture for solar protection and aesthetic purposes. Le Corbusier demonstrated the modern application of shading devices in Unit De Habitation and Capital complex in Chandigarh, which allowed his buildings to respond to the tropical climate (Kamal, 2022). The influence of modern architecture with traces of climatic adaption expanded to Southeast Asia and Thailand in the 1950s, which inspired local architects to create a series of climatically adaptive modern-style architectural forms (Charoenphol et al., 2020; Leu & Boonyaputthipong, 2023). Shading devices have been drawing increasing research attention in modern applications since the 1990s (Kirimtat et al., 2016). The common way to deploy shading devices is to install them over transparent surfaces to reduce solar radiation heat gain; thus heat, lighting and window-to-wall ratio (WWR) are common issues of concern (Bellia et al., 2013; Ferdous & Gorgolewski, 2014; Koç & Maçka Kalfa, 2021; Pino et al., 2012; Poirazis et al., 2008).

Shading device experiments using actual models incur budget issues, with a long research completion period in order to conduct comprehensive climatic cycle investigations through a year. Kirimtat et al. (2016) discussed the importance of computer simulation for shading device research. Parametric studies of shading device performance have been conducted for various contexts using building energy modelling software (Bellia et al., 2014; Kirimtat et al., 2016). Various software options exist for such modelling, including Transys, DOE-2, IES_VE, TAS, ESP-r, Lightscape, Fluent, DIVA, Ecotect, Radiance, and IENUS, but EnergyPlus (E+) is the most frequently employed (Kirimtat et al., 2016).

Shading is crucially important for buildings in hot climates with high levels of solar radiation. Vegetation screening is the most natural way by which to reduce solar radiation and reduce heat gain (Baker, 1987). Analyses of vegetation screening have highlighted the benefits of shading in reducing surface temperature, but the presence of vegetation entails maintenance costs for buildings as well as the vegetation itself (Berry et al., 2013; Laopanitchakul & Srisutapan, 2007). The mass of buildings themselves can be designed and utilized to avoid exposing surfaces directly to radiation, which is known as a self-shading technique. Kandar et al. (2019) investigated the benefit of the self-shading design that inclined glazed façades under the hot and humid climate of Malaysia. The results revealed that higher percentages of wall self-shading projection were linked to lower amounts of solar radiation on building surfaces and reduced heat gain. The optimum self-shading projection of inclined walls was 45%. However, the self-shading technique for opaque surfaces has not attracted significant research attention, and a lower number of relevant publications could be found while conducting this study. Most related research has focused on localized solutions rather than techniques *per se*.

Wati et al. (2015) investigated the effect of shading on the thermal performance of walls under the tropical climate of Douala, Cameroon. The results demonstrated the importance of shading to decrease the cooling load and heat flux of walls. A larger percentage of shade on the walls, was associated with a smaller thickness of optimal insulation depth. Shahda (2020) employed Design Builders software to investigate the thermal performance of nature-inspired self-shading walls in a hot and dry climate. Three surface patterns were examined for the east, west, and south-facing façades. The results demonstrated a reduction of external and internal surface temperatures resulting in a decrease in the total difference in surface temperature (ΔT). Liu et al. (2019) also conducted simulation research using Design Builder to investigate the energy-savings potential of shading panels on opaque walls in Hong Kong. A total of 252 simulations were analyzed using scatter plots. The relationship between device area (m^2) and energy saving (%) was analyzed with the Hill equation to identify the best-fit curve, where the elbow of the curve was used to identify the optimal performance condition. The optimal shading configuration can reduce energy demand by up to 8%. Real environments were studied to explore shading created by different patterns and extrusions by Sippapakul and Sreshthaputra (2017). The conclusion of their study suggested that more extended patterns resulted in lower surface temperature, while the variation of the pattern exerted less impact on the surface temperature.

Furthermore, the U-value of the wall is dynamic and varies according to the size of the surface shadow (Sippapakul & Sreshthaputra, 2017). Such a dynamic U-value also affects the calculation of the Overall Thermal Transfer Value (OTTV), which is included in Thailand's Building Energy Code (BEC). Energy and sustainability issues are a concern for the Thai government, with the Ministry of Energy issuing a ministerial regulation regarding BEC, according to which new building construction having an area greater than 2000 m^2 (e.g., hotels, condominiums, offices, and schools) must submit an energy conservation report pertaining to the building (Ministry of Energy, 2022; The Association of Siamese Architect under Royal Patronage, 2022). This report must address issues of heat transfer for the building envelope, minimum coefficient of performance for air conditioning and water heating systems, the power density of the lighting system, and net energy consumption.

The BEC section on the heat transfer of the building envelope considers crucial calculations pertaining to OTTV and Roof Thermal Transfer Value (RTTV). The total heat transfer value equations for transparent surfaces consider the benefit of the shading, reflecting the acknowledgement that shading per se exerts a tremendous impact on the total OTTV and RTTV values; however, despite the heat-reducing advantage of shaded opaque façades, the algorithm in BEC seems to exclude its importance.

The self-shading technique using building mass, shading devices, and complex surfaces is crucial for tropical architecture and can shape building appearance and characteristics, thereby enhancing occupants' well-being. Therefore, this study focuses mainly on the shading benefit of opaque wall surfaces to explore the degree of solar radiation reduction caused by overhang shading devices with different configurations and to suggest an optimum device depth-to-space (Ds) ratio.

This research aims to highlight the benefit of shading devices on opaque walls in reducing total wall solar radiation heat gain and discover an optimum depth-to-space ratio of overhang shading devices associated with opaque walls for all façade directions. To achieve this, we seek to: (1) investigate solar radiation of benchmark model surfaces with 12 different configurations of overhang shading devices (OH) based on Bangkok climatic conditions, to explore the optimum Ds ratio; and (2) examine the obtained configurations using device depth before the results are discussed and conclusions drawn.

2. Research Method

2.1 Environmental Context

This study investigates building thermal performance using a benchmark model having typical dimensions generally found in large residential units and public spaces in Thailand: 6 x 6 x 6 m (depth, width, and height, respectively). The model was elevated 6 m above ground level to prevent earth contact, as ground heat exchange was not analysed in this study.

The environmental condition of the model was set for Bangkok (13.92 latitude and 100.6 longitude), which has a tropical savanna climate (Aw) as classified by the Köppen-Geiger system (2019) and displayed in Figure 1. IWECC weather data for Bangkok obtained from the E+ website (Energyplus, 2023) were applied for the simulations, without internal gain and air-conditioning systems. Based on the E+ information, the maximum and minimum monthly outdoor temperature (T_{out}) values are 30.6°C in April and 26.4°C in December (respectively); the relative humidity (RH) is 81.0% in October and 57.7% in December.

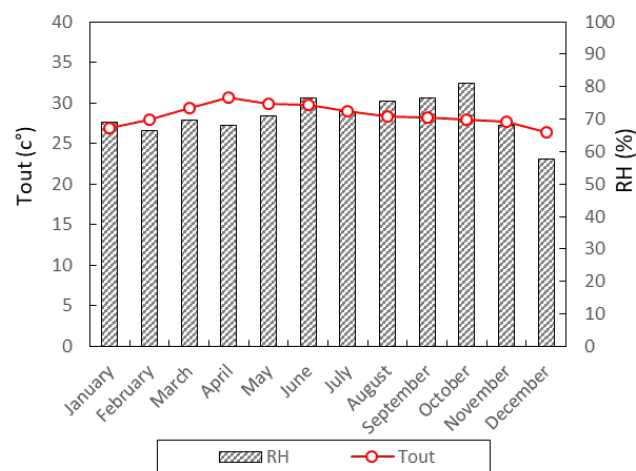


Figure 1 Bangkok climatic data

Often, cloud extent is evaluated according to the oktas scale ranging from one to eight, where 8=sky obstructed from view and four is sky half cloudy (Ahmad et al., 2018; Met Office, 2018). However, E+ reports a wider range of cloud extent, ranging from zero (0=minimum) to ten (10=maximum) (Bigladdersoftware, 2018). The E+ information revealed that Bangkok's sky is partly cloudy since the annual average sky cover is 6.9. Sky cover variation and diffuse solar radiation rate vary correspondingly, changing in inverse proportion to the direct solar radiation rate. The direct solar radiation ranges from 56.59 W/m² in August to 181.86 W/m² in March while the diffuse solar radiation ranges from 82.71 W/m² in December to 141.29 W/m² in May. Sky cover varies between 4.92 in January to 8.87 in August, as shown in Figure 2.

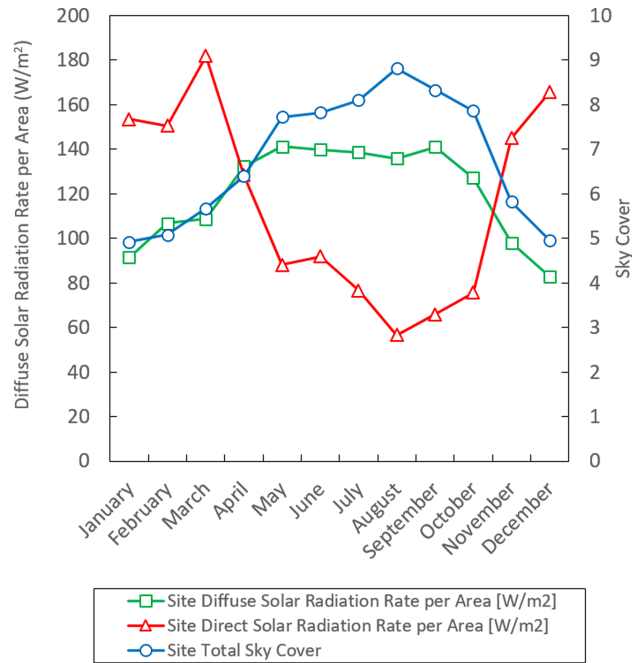


Figure 2 Bangkok solar radiation data and sky cover

2.2 Simulation Configurations

This research employs Sketchup with Elucid extension to generate geometries, assign model material properties and create thermal zones. E+ is widely employed in research practice (Bellia et al., 2014; Kirimtat et al., 2016) and is endorsed by the U.S. Department of Energy (U.S. Department of Energy, 2023b), thus it was selected for use in this study. E+ utilizes shadowing algorithms based on BLAST and TARP to analyze shading effects in relation to solar positioning. Moreover, the terrain of the ‘city’ is set for simulation with the ‘FullinteriorAndExterior’ feature, to consider the impact of beam solar radiation on both the interior and exterior building surfaces as part of the calculation (Liu et al., 2019; U.S. Department of Energy, 2023a). E+ considers the solar radiation on exterior surfaces (Sr), encompassing the angle surface to sky and surface to ground factors, combined with the three main solar radiation factors: namely beam radiation (Sb), sky diffuse radiation (Skd), and ground diffuse radiation (Sgd). Documentation Engineering Reference provides more information about solar radiation algorithms (U.S. Department of Energy, 2023a).

2.3 Two Investigation Phases

This study was divided into two phases: (1) investigate the performance of device depths on exterior wall surfaces to identify the optimum device depth and spacing (Ds) ratio; and (2) examine the optimum Ds ratio using different depths of the device. The first phase was a parametric study of the benchmark model attached with overhang shading devices (OH) extending from the wall surfaces. It should be mentioned that the shading device was assigned with a non-heat transfer material. The building materials consisted of 10-cm thick brick walls with plaster render and concrete floor and roof, as presented in Table 1. The results of the first phase were analysed to explore the optimal Dd and Ds ratio for the second phase. The walls were horizontally divided into 13 segments (with a gap of approximately 46.15 cm between each OH device) for OH attachment, as shown in Figure 3.

Table 1 Building surface details of the benchmark model

Surface	Component	Thickness, L (cm)	Conductivity, λ (W/m.K)	Density, d (kg/m ³)	Specific Heat, c (J/kg.K)
Brick wall with plaster render	10-cm brick wall	10	0.6	1300	900
	2 layers of plaster render (internal and external surfaces)	10 mm (each layer)	0.23	800	840
Concrete floor	20-cm concrete slab	20	1.7	2200	840
Concrete roof	20-cm concrete slab	20	1.7	2200	840

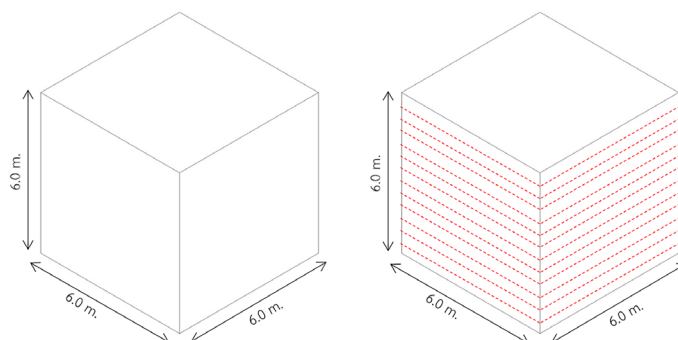


Figure 3 Benchmark model with segmentation lines for OH shading device configuration

The modelling included twelve configurations of OH devices with non-heat transfer material attached at the north, east, south, and west walls, extended with 10.0-cm intervals ranging from 10.0 to 120 cm, as shown in Figure 4. The upper limit of the Dd (120 cm) is the maximum typical width of material panels available in Thailand (120 cm width by 240 cm length). The second phase of the study examined Dd based on the optimum Ds ratio. Six Dd values of OH devices were created and simulated based on the optimum Ds ratio. Data were statistically analysed using Microsoft Excel and IBM SPSS.

Overhang Shading Device Configurations			
10 cm.	20 cm.	30 cm.	40 cm.
50 cm.	60 cm.	70 cm.	80 cm.
90 cm.	100 cm.	110 cm.	120 cm.

Figure 4 OH device configuration for the first study phase

3. Results

3.1 The Benchmark Building Simulation

Solar radiation on surfaces varies according to the tilt angle of the sun. E+ provides the condition of solar radiation on the benchmark building façades, whereby the roof surface is perpendicular to the sun, demonstrating the greatest Sr rate (203.75 W/m^2), consisting of Sb (83.42 W/m^2) and Sgd (120.33 W/m^2). The floor surface raised 6.0 meters above the ground exhibited the smallest rate of radiation, caused mainly by Sgd (40.74 W/m^2).

The wall surface is affected by three solar radiation factors, namely Sb, Skd, and Sgd. It should be noted that in the case of Sgd on walls, E+ assumes that Sgd is distributed uniformly across the walls. Therefore, the results reported an even Sgd of 20.37 W/m^2 , while Sr and Skd rates changed according to face directions (Figure 5). The north-facing surface presented the smallest Sr rate (68.98 W/m^2) among the wall surfaces due to low Skd (44.49 W/m^2), with the lowest Sb (4.11 W/m^2). The rate of Sr on the other wall orientations showed small differences of 102.78, 104.13, and 107.16 W/m^2 due to small variations of Sb (26.62, 27.65, and 32.14 W/m^2) and Skd (55.78, 56.11, and 54.65 W/m^2) for the west, east, and south-facing façades, respectively.

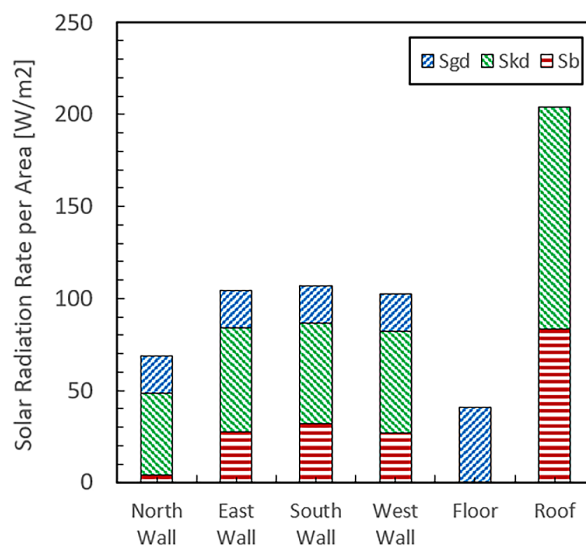


Figure 5 Solar radiation rate per area on different surfaces of the benchmark model

3.2 First Study Phase

3.2.1 Performance of OH devices

OH devices were installed in the benchmark model with depths ranging from 10 to 120 cm to investigate device performance on the baseline model, in order to identify the optimum Dd values. The latter were plotted against Sr on the different wall orientations, as shown in Figure 6, which demonstrates that the depths of the OH devices relate inversely with Sr in all directions of the façades.

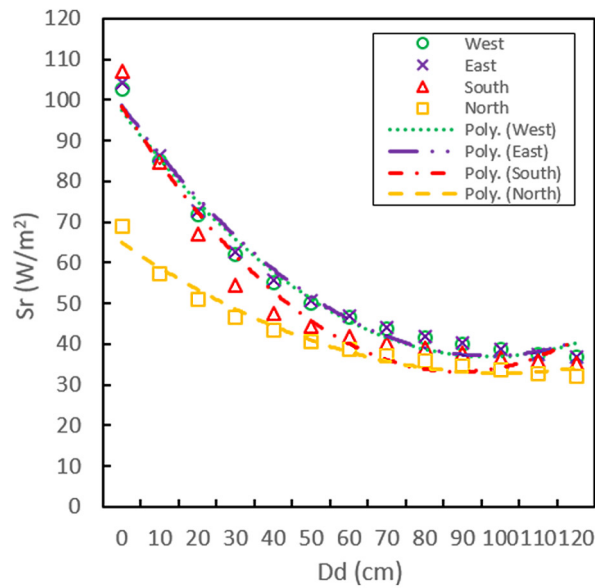


Figure 6 Quadratic regression of Sr on different directions of wall surfaces

The regression analyses based on linear, quadratic, and exponential models were used to explore the relationship between the stepwise increase of Dd and Sr rate. The significance levels of all independent factors were less than 0.00 ($p < 0.01$) in all cases (Table 2). The linear model does not fit the data as well, since the Coefficient of Variation (R^2) shows moderate fit, ranging from 0.72 to 0.83, which is lower than that of the curvilinear, namely quadratic and exponential regressions. This study found that quadratic regression demonstrates the strongest relationship between Sr and Dd, reflected in the highest R^2 for all cases ($R^2 > 0.97$). Furthermore, the coefficient for Dd^2 revealed the highest value (0.0082) of the south-facing façade among the factors. This represents the superior solar blocking capability of the OH device on the south façade. On the other hand, the north-facing façade showed the least reduction with an increase in OH depths, due to its smaller coefficient of Dd^2 at 0.0032.

Table 2 Regression analyses of Sr and Dd on the benchmark wall surfaces in different orientations

Orientation	Model	Equation	R^2	p
North	Linear	$Sr = -0.2564Dd + 57.886$	0.830	< 0.001
	Quadratic	$Sr = 0.0032Dd^2 - 0.638Dd + 64.883$	0.971	< 0.001
	Exponential	$Sr = 58.258e^{-0.006Dd}$	0.903	< 0.001
East	Linear	$Sr = -0.4853Dd + 84.382$	0.818	< 0.001
	Quadratic	$Sr = 0.0065Dd^2 - 1.2684Dd + 98.74$	0.981	< 0.001
	Exponential	$Sr = 85.459e^{-0.008Dd}$	0.908	< 0.001
South	Linear	$Sr = -0.4778Dd + 80.343$	0.715	< 0.001
	Quadratic	$Sr = 0.0082Dd^2 - 1.4672Dd + 98.482$	0.949	< 0.001
	Exponential	$Sr = 79.389e^{-0.008Dd}$	0.821	< 0.001
West	Linear	$Sr = -0.4757Dd + 83.255$	0.816	< 0.001
	Quadratic	$Sr = 0.0064Dd^2 - 1.2476Dd + 97.406$	0.981	< 0.001
	Exponential	$Sr = 84.251e^{-0.008Dd}$	0.908	< 0.001

Furthermore, the S_r value was analyzed based on its components consisting of S_b , S_{kd} , and S_{gd} (U.S. Department of Energy, 2023a). The analytical results are displayed in Figure 7, which illustrates the solar radiation components plotted against D_d . Noticeably, an increase in D_d exerted no impact on S_{gd} since E+ assumes that S_{gd} is distributed uniformly across the walls, while greater D_d values lead to a reduction of S_b and S_{kd} , which produced a drop in S_r (Figure 7(A)). A superior S_r , S_b , and S_{kd} protection with considerable increase of radiation rate appeared when configuring the model with the 10 cm device. The performance of the sun protection, in contrast, increased gently with a decay behaviour as the magnitudes of radiation rate were reduced since the differences between the radiation factors and D_d were gradually smaller compared to their values of 10 cm narrower D_d . A decrease in S_r due to the increase of D_d resulted in heat gain reduction on exterior building surfaces, which reduces the annual average indoor air temperature (T_{in}). The reduction in T_{in} therefore shows a similar negative decay curve as the S_r , S_b , and S_{kd} graphs (Figure 7(B)).

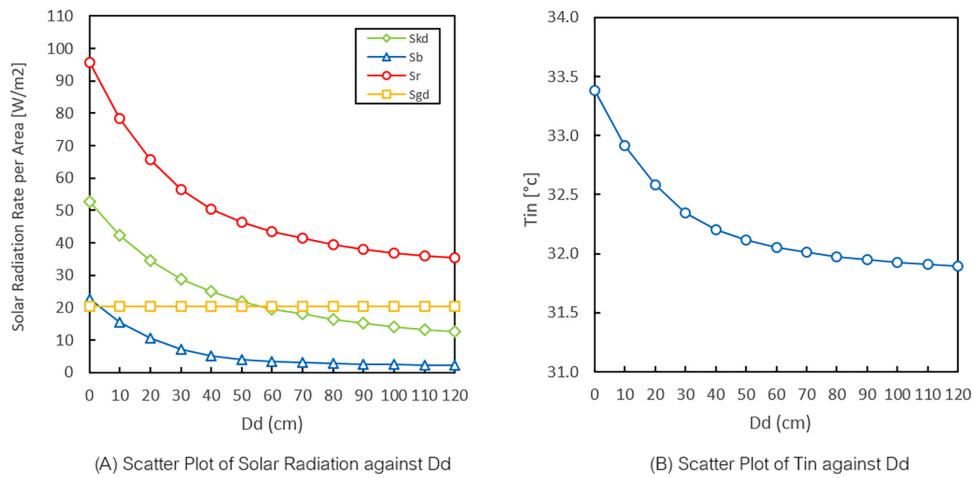


Figure 7 Scatter plots of observed factors of S_r , S_b , S_{kd} , and S_{gd} (A), and T_{in} (B) against D_d

3.2.2. Optimum D_d analysis

An increase of T_{in} resulting from heat gain of exterior building surfaces was mainly affected by S_r , which consisted of S_b , S_{kd} , and S_{gd} . S_{gd} distributed uniformly across the walls was excluded in this analysis due to its constant behaviour, disregarding a variation in D_d across OH device configurations. Therefore, this section discusses an optimum D_d investigation based on T_{in} , S_r , S_b , and S_{kd} . The variables were analysed using percentage differences between the values of the baseline model subtracted from the observed model. Each deducted value was divided by the greatest value difference of 120-cm OH variables, which was considered 100% for this study. This method allowed investigation of the performance difference of each OH configuration compared to the baseline model. The discussed variables' percentage differences are $T_{in, \text{diff. baseline}}$ for T_{in} , $S_{r, \text{diff. baseline}}$ for S_r , $S_{b, \text{diff. baseline}}$ for S_b , and $S_{kd, \text{diff. baseline}}$ for S_{kd} . Each data set consisted of 12 values based on the model configurations, with D_d of OH varying as from 10 to 120 cm, as shown in Figure 8.

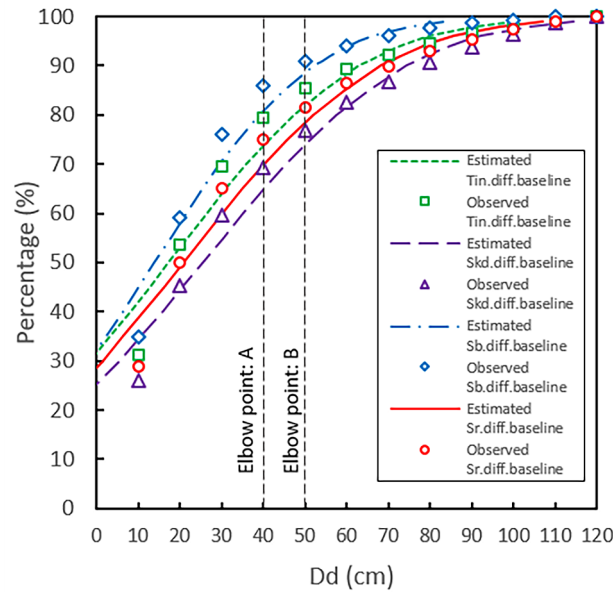


Figure 8 Probit analysis of observed and estimated values of $T_{in,diff,baseline}$, $Sb_{diff,baseline}$, $Sr_{diff,baseline}$, and $Skd_{diff,baseline}$

It should be noted that the deeper the OH device, the larger the difference between the baseline model and the observed value. Thus, the coordination of each factor started at 10 cm OH, and reached 100% at 120 cm OH. The relationships between Dd and the percentage (Pct) of the factors were analysed using a probit model. Probit regression demonstrates a sigmoid curve with decay slopes at both ends of the estimated lines (Figure 8). The Pearson goodness-of-fit test was employed to analyse the probit model based on the hypothesis test conditions of the null hypothesis (H_0), indicating that the estimated and observed values are fitted. The significance levels (p) of Chi-square statistics found in this study were more than 0.05 ($p > 0.05$) in all cases: 0.325 ($T_{in,diff,baseline}$), 0.306 ($Sb_{diff,baseline}$), 0.503 ($Sr_{diff,baseline}$), and 0.657 ($Skd_{diff,baseline}$) (The Pennsylvania State University, 2023). Therefore, the significance levels necessitate the acceptance of the H_0 , confirming the relationship between the data sets.

The data were characterised through the non-linear relationship of a sigmoid curve (Liu et al., 2019). To identify the elbow point for the optimum values, this study refers the methodology recommended by Delgado et al. (2015). A straight line was used to connect the first and the last values; then, the elbow point referred to the longest distance of the perpendicular vector between the straight line to the observed value. The analytical results show that the optimum Dd values are 40 cm for $T_{in,diff,baseline}$ and $Sb_{diff,baseline}$, and 50 cm for $Sr_{diff,baseline}$ and $Skd_{diff,baseline}$, as presented in Figure 9 (for elbow points A and B).

According to the results, two elbow points (40 and 50 cm) can be discerned. Elbow point A is used to set the optimal value for this study, since T_{in} is one of the main concerns for indoor thermal comfort and the consequence of heat flux reduction due to solar radiation. The 40 cm OH reduces the annual average of T_{in} by 3.53% (1.18°C) (see Figure 10) compared to the benchmark model, or 79.44% compared to the 120 cm OH performance (at maximum 100% performance) for this study (see Figure 8). This 40-cm Dd with the default spacing of 46.15 cm can be converted to an optimum Ds ratio of 1:1.15.

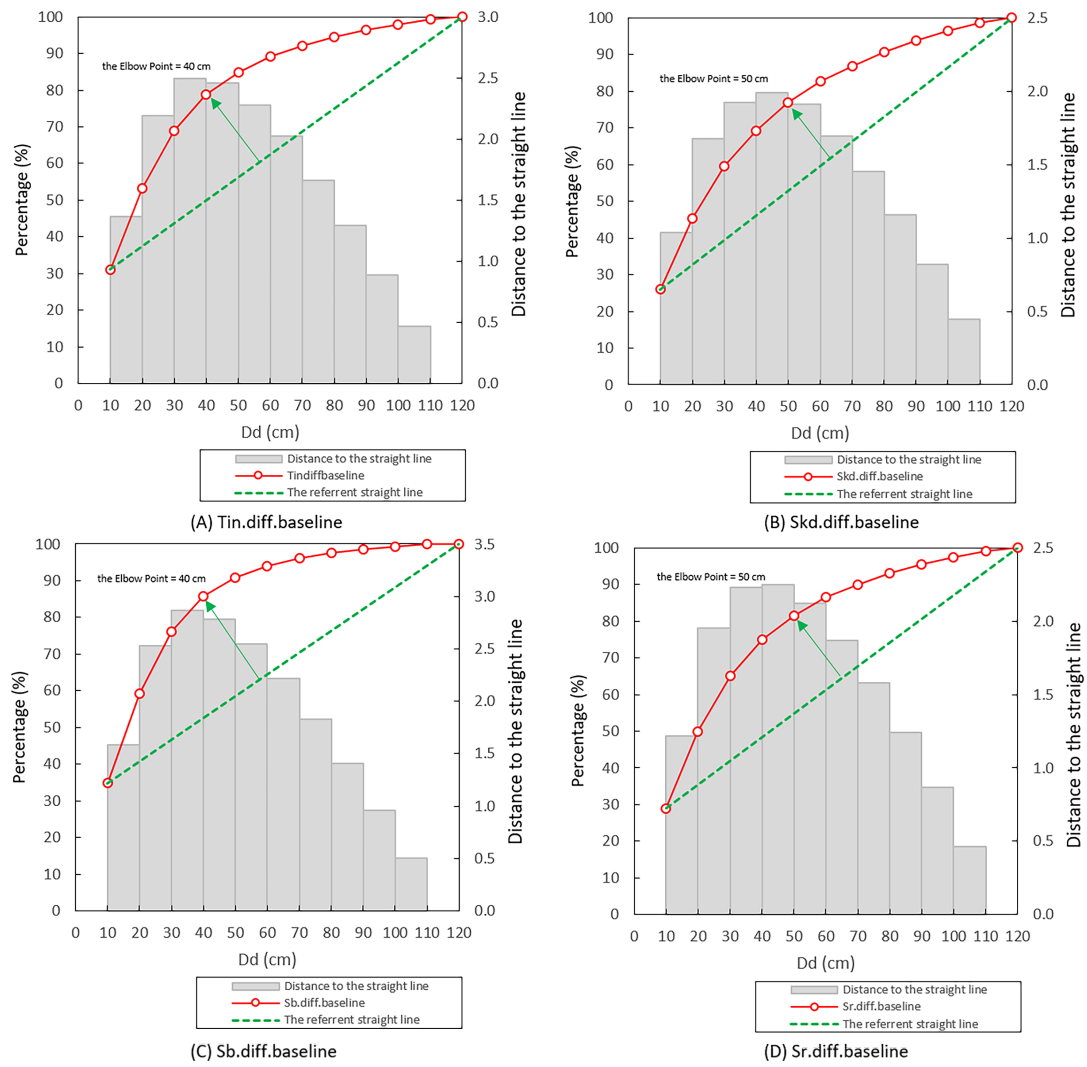


Figure 9 Optimum D_d of OH analysis by elbow method

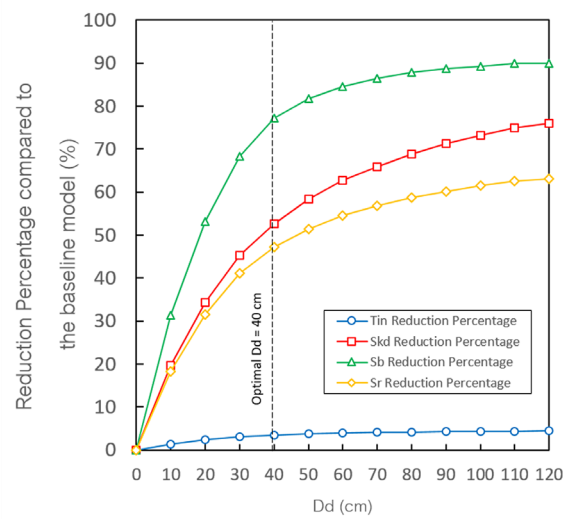


Figure 10 Reduction percentage according to increase in D_d

3.3 Second Phase: Performance of Ds Ratio Examination

The optimal 1:1.15 ratio was examined by varying the number of wall segments from 11 to 15 for shading device installation (Figure 11). The spaces (S) between each device were 40.00, 42.86, 46.15, 50.00, and 54.55 cm, with proportional Dd of 34.7, 37.1, 40.0, 43.3, and 47.3 cm, respectively.

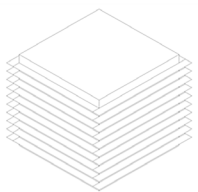
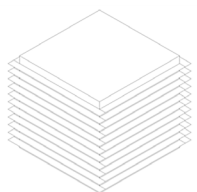
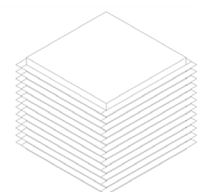
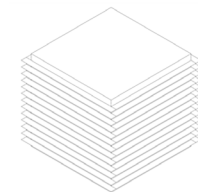
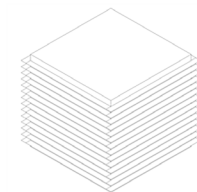
1/1.15 Ds Ratio Mass Configuration									
No. of Segment: 11		No. of Segment: 12		No. of Segment: 13		No. of Segment: 14		No. of Segment: 15	
Depth = 0.41	Space = 0.86	Depth = 0.36	Space = 0.75	Depth = 0.32	Space = 0.67	Depth = 0.29	Space = 0.60	Depth = 0.26	Space = 0.55
									

Figure 11 Model configurations of 1:1.15 DS ratio

The analytical results based on the six sets of OH configurations reveal minor Tin, Sr, Sb, and Skd differences between the 11 and 15-segment models by 0.03 °C, 1.2 W/m², 0.4 W/m², and 0.72 W/m², respectively (Figure 12).

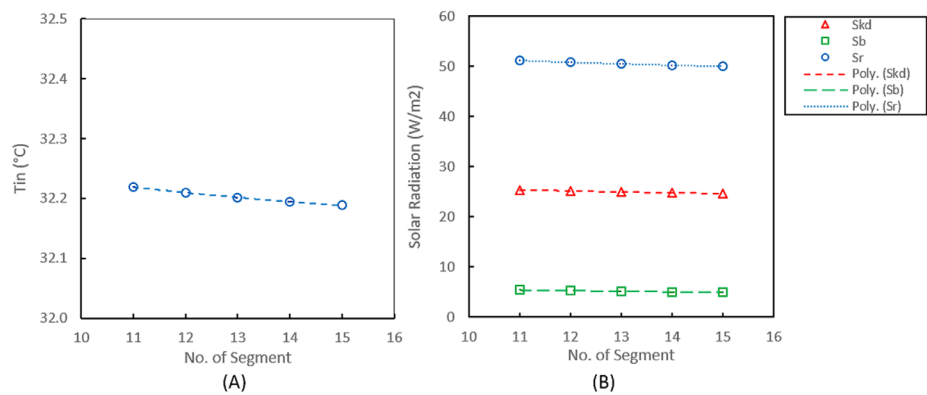


Figure 12 Relation of Ns and Tin (A) and solar radiation (B)

The analyses based on linear, logarithmic, quadratic, power, and exponential regressions revealed high R^2 ranging from 0.99 to 1.00, with a significance level of less than 0.001 ($p < 0.001$). The quadratic regression for all variables formed the highest R^2 value of 1.00 ($R^2 = 1.00$). Such a relation indicates a low sensitivity to a change in the number of the segments (Ns) under the same optimum Ds ratio, due to the minimum coefficients for a square variable of each factor, as displayed in Table 3: 0.0005 for T_{in} , 0.0173 for Sr, 0.0097 for Skd, and 0.0075 for Sb.

Table 3 Relationships between Tin, Sr, Skd, and Sb and Ns

Equation	R ²	p
$T_{in} = 0.0005N_s^2 - 0.0206N_s + 32.385$	1.00	<0.001
$S_r = 0.0173N_s^2 - 0.7401N_s + 57.21$	1.00	<0.001
$S_{kd} = 0.0097N_s^2 - 0.4351N_s + 28.988$	1.00	<0.001
$S_b = 0.0075N_s^2 - 0.305N_s + 7.8518$	1.00	<0.001

A minor difference of variables over the Ns growth is caused by unshaded areas in the corners. Based on the study of the optimum Ds ratio study, the deeper the OH device is, the more unprotected the wall surfaces of the building are at its corners. However, it should be noted that the difference found in this research regarding the Ns is minimal compared to changing the Ds ratio.

4. Discussion

Sr consisting of Sb, Skd, and Sgd is an environmental factor of great concern to architects designing tropical buildings, potentially causing excessive heat gain from building fabrics. According to the weather data, Bangkok's sky often is obscure, causing relatively high diffuse solar radiation. An Sb-protecting strategy to avoid exposing building surfaces may be insufficient and diffuse solar radiation should be taken into account. The OH shading device investigated in this study not only screens Sb, but also Skd.

The cost of construction for shading devices varies according to the details of design, methods of installation, and materials. Excessive material usage affects the construction cost and may involve sustainability issues in terms of construction wastes and natural resources. The optimum Ds ratio (1:1.15) identified in this study suggests that a larger depth of OH device installation is not necessary. The performance of the OH devices considerably increased in relation to Dd in the first OH configuration (10 cm). However, after a certain depth, its performance increased only slightly. The capacity for indoor temperature reduction relates to the amount of energy consumption for active cooling. Thus, if an air-conditioning system is required, shading on opaque surfaces by OH is supposed to reduce the burden of the cooling operation, consist with the findings of Wati et al. (2015) and Liu et al. (2019). The decay in performance behavior after the optimal point of the shading devices agrees with the previous study of Liu et al. (2019). Considering the constraint of construction cost or appropriate appearance of the façade design, smaller ratios than the 1:1.15-Ds ratio still provide acceptable solar protection since the protective performance starts to improve significantly in the first depth of installation (10 cm), and continues to improve until the optimal depth.

The optimal Ds ratio can be applied to develop building envelope products which aim to improve building thermal performance. The devices are, besides, considered as a decorative element of exterior surfaces which can be designed with various profile sections, colors, materials, textures, and arrangements. For the thermal performance of the shading devices on opaque walls, it should be noted that the simulations discussed in this study assigned a non-heat transfer property to the thin shading devices. In reality, creating building shading devices with no thermal bridge, whose heat transfer properties are comparable to the results of this study, appears to be a challenging task. Therefore, it is recommended to use low thermal conductivity materials for OH devices. Furthermore, reducing the contact area between the OH panels and building surfaces by inserting insulation to create separation also decreases the heat flux between the two materials.

This study demonstrates the advantages of shading in reducing solar radiation on exterior opaque walls, consequently lowering interior air temperatures and impacting cooling energy demand. In addition to creating wall shading with OH devices, various techniques can be employed. Wall textures can be constructed using brick masonry with extrusion patterns to create a self-shading façade. The technique, introducing a series of brick wall patterns with an analysis of thermal performance, was discussed by Shahda (2020), Sippapakul and Sreshthaputra, (2017), and Tarabieh et al. (2017). Another application is a brick-relief that creates depth and shadow patterns as shown in Figure 13 (A), which presents a building façade of Victoria Gate, Leeds, UK designed by ACME. Shading created by depths and rhythms using precast concrete cladding can prevent certain areas of the façade from being exposed to solar radiation, with Figure 13 (B) showing a precast façade of Nottingham Contemporary Museum, Nottingham, UK designed by Caruso St John Architects.

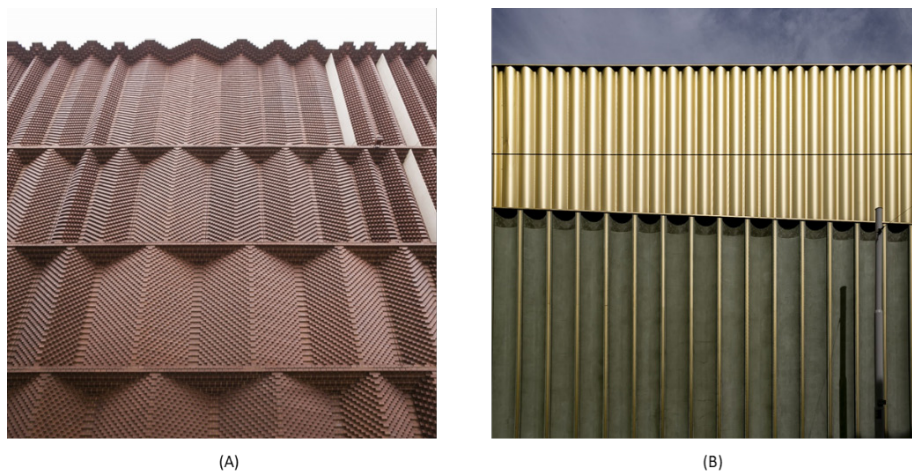


Figure 13 (A) Brick-relief façade of Victoria Gate, Leeds, UK and (B) concrete cladding façade of Nottingham Contemporary, Nottingham, UK

Furthermore, in terms of architectural aesthetics, instead of leaving building surfaces with plain walls, shading devices on opaque walls and relief façades can be considered as decorative elements to enhance textures and patterns of building envelopes in tropical architecture. This alternative approach allows architects and designers to embellish building facades while enhancing thermal performance.

With regards to the Thai Building Energy Code (BEC), it is widely accepted that transparent surfaces are one of the key contributors to external heat gain. Transparent building envelopes have become the focal point for building design for solar radiation protection. The importance of glazing surface protection using shading devices is acknowledged by the BEC and is included in the equation for OTTV. This calculation incorporates a Shading Coefficient (SC) for transparent surfaces to represent the solar-protective ability provided by shading devices. However, the benefit of opaque wall shading, as discussed in this study, currently is excluded, as the calculations focus primarily on wall thermal properties such as U-value (U), wall thickness, density (ρ), and specific heat capacity (C_p).

Thus, this study highlights the benefits of shading on solid walls and suggests an improvement for the BEC by incorporating the effect of opaque wall shading. However, to achieve this, solutions to correct the OTTV equation are required, along with additional empirical supporting data. These aspects can be considered research gaps, demanding further investigation.

5. Conclusion

Vernacular Thai architecture employs various heat avoidance techniques, such as extra-long eaves with supports, clustered terraces for shading, and the use of environment shade such as trees and proximate buildings. Such architectural solutions demonstrate how local communities traditionally relied on passive cooling and natural building materials and vegetation. Architects in the tropics can learn to create buildings with more concern for and incorporation of the natural context. Solar radiation is one of the crucial factors causing thermal discomfort which is a hindrance to wellbeing and shading devices can be employed to alleviate related challenges. Shading devices are an indispensable element of tropical architecture.

This simulation-based study employed E+ and SPSS to investigate the performance of overhang shading devices on opaque walls in Bangkok. Its two phases focused on (1) the benchmark building analysis under Bangkok climate and parametric study of the device depth on the benchmark building to explore the optimum depth-to-space ratio; and (2) the examination of the depth-to-space ratio under the same proportion of device depth and spacing. The salient findings are as follows:

- Beam solar radiation contributes the highest magnitude at the roof, followed by the south-facing façade, which is slightly higher than that of the east and west-facing walls, and presents a comparable radiation rate.
- Building wall surfaces face a heat gain challenge in Bangkok largely resulting from solar radiation diffusion from the sky and the ground, due to the annual sky clearness of 6.9, where the maximum score of 10 represents full cloud cover.
- It is recommended to shade opaque walls to decrease input of solar radiation. The self-shading of walls using overhang devices greatly reduces interior air temperature and exterior surface radiation. The deeper the device depth is, the better its solar-screening capability and heat reduction performance. The optimum device depth is characterized by the 1:1.15 depth-to-space ratio, which reduces the annual average indoor temperature by 3.53% (1.18°C) compared to the benchmark model or 79.44% performance in T_{in} reduction (compared to the 120-cm overhang shading device, which was considered to yield 100% maximum performance compared to the baseline model in this study).
- Deeper device depths than the optimum depth-to-space ratio can be applied, with a slight improvement in protective performance (and commensurately increased costs).
- The optimum ratio provides the most efficiency in reducing indoor temperature and minimizing solar radiation input. The performance remains comparable when modifying the dimensions of shading devices based on the optimum ratio, while varying the ratio leads to a noticeable change in solar protection performance.

This computer-based study requires verification with experimentally-based results conducted in real application conditions. It is necessary to conduct experiments with physical models under actual climates to investigate real-life thermal behavior and its impact on interior spaces. Besides, this study demonstrates the benefits of shelf-shading walls using overhang devices for the hot tropical climate of Thailand. It is suggested that the impacts of other types of shading devices, such as fin and egg-crate shading models, also should be evaluated.

Apart from investigating thermal performance of shading devices for solid walls, the results of this study can be applied in the development of building envelope products aimed at enhancing thermal performance and decorating buildings with wall textures and shading patterns. In addition to the OH form, opaque walls can be designed using different techniques such as brick extrusion and brick relief.

Finally, this study highlights the benefits of shading on solid walls and suggests an improvement for BEC by incorporating the shading effect of opaque walls. However, to achieve this, solutions to correct the OTTV equation are still required, along with additional empirical supporting data. These aspects can be considered research gaps, requiring further investigation.

Author Contributions

T.S. contributes 100% of the work appears in the paper including finding the research gaps, setting up the research method, conducting literature review, creating graphics, conducting the simulations and statistic analyses, and writing.

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