Influence of inclined wall self-shading strategy on office building heat gain and energy performance in hot humid climate of Malaysia

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ABSTRACT

External shading geometry on buildings has been found to contribute substantially to reducing energy consumption for cooling. This study examines the effect of inclined wall self-shading strategy on heat gain in an office building. Field measurement of environmental variables such as ambient temperature, relative humidity, dew point, and wet bulb temperature was carried out in a case study inclined wall self-shading office building located in Putrajaya, Malaysia. The results of the validation of ApacheSim simulation software tool against the measured environmental variables indicated significant reliability having Pearson correlations ranging from 0.56 to 0.90. In establishing the relationship between different inclined wall strategies to the amount of heat gain, modification of the inclined wall self-shading projection (SSP) was modelled and experimented using ApacheSim simulation. Findings from the analysis revealed a relationship between heat gains into a building space and self-shading projection (SSP), as heat gains tend to reduce with increased SSP. From the findings, the optimum inclination angle of self-shading for effective heat gain reduction is based on a 45% self-shading projection. The application of inclined wall self-shading strategy in buildings would, therefore, bring about a reduction in heat gain, which invariably reduces energy consumption for cooling.

1. Introduction

Wall shading strategy in buildings is one of the passive design strategies to minimize the direct impact of sunlight on a building facade as a means of reducing solar heat penetration in buildings, especially, in the tropics (Chia, 2008). The building envelope is its external parts through which radiant heat is conducted into the indoor building spaces. Consequently, buildings are expected to have an outer skin that prevents or reduce heat penetration (Malaysian Standard, 2007). The increase in energy demand is not at parity with available natural resources, therefore, resulting in higher energy cost. The design and construction of buildings to promote sustainable environment have been reinvigorated especially, by applying appropriate technology and methods. A decrease in energy consumption can be attained using both the user-based and infrastructure-based method. The user-based method involved changing the building occupant's behavior as regards a reduction in energy demand regarding efficiency yield, while the infrastructure-based method involved building designs that have less energy demand in their functional requirements. The passive design of buildings has consequently, translated into an improvement in the buildings natural ventilation and thermal insulation.

Sustainable buildings and the efficient use of energy in recent times have turned out to be main subjects of critique which requires much attention to be committed to it (Marszal et al., 2011). One of the top sectors in energy demand and depletion particularly in countries with higher urbanization rate and standard of living is the building industry (Xin and Rao, 2012; Zhao et al., 2010). In tropical Malaysia for example, cooling account for most of her energy consumption. For instance, a study carried out by Chan (2004), have shown that air-conditioning alone takes about 64% of energy demand in a typical office building in Malaysia, because of it hot and humid climate. Other building services such as lighting and general equipment take the remaining percentage in the ratio of 2:1 respectively. Saidur (2009) on the other hand have affirmed that the energy consumption for air-conditioning in buildings in Malaysia takes 57% while lighting makes 19%, which contradicted Chan's assertion. However, these study outcomes are indicative of the necessities to reduce energy consumption in Malaysian office buildings by applying energy-efficient strategies.

As a result of high energy cost and its environmental impact, energy consumption in buildings needs to be reduced both at the conceptual

design stage and the building in use. Research has shown that energy demand in buildings can be reduced where specific energy efficient innovations are employed in the building design (Cambiaso, 2013). For sustainability to be achieved in the design of green buildings, the need to carry out building modelling and simulations using computer-aided tools have been alluded (Cambiaso, 2013). Nevertheless, most architectural design of buildings tends towards aesthetic values rather than the design of buildings to respond to climatic elements thereby reducing heating and cooling loads (Sulaiman and Hassan, 2011a). Consequently, several types of research have been carried out in Malaysia to develop strategies that can minimize the demand for energy for cooling in (Bhaskoro and Gilani, 2011; Kwong et al., 2009; Sulaiman and Hassan, 2011b). Through some of these studies, some forms of modifications to building facades such that would reduce heat gain into the building by direct sun rays especially in highrise buildings have been suggested (Capeluto, 2003; Chia, 2008). One of these modifications is self-shading in buildings, which reduces the impact of solar radiation on the building indoor spaces.

There have also been efforts towards constructing "Zero Energy Building (ZEB)" with no carbon and energy footprints (Todorvic, 2012). In Malaysia today, there exist about three prominent energy efficient office buildings which have been adjudged to achieving less energy demand in comparison to other typical office buildings (Chan, 2009; Kandar, 2005). The successes recorded as result of the design and construction of these buildings have brought about increasing awareness and concern by both government and policymakers, and also researchers, towards the promotion of energy efficiency in buildings.

Heat penetration into a building can be influenced by the building form, location, orientation, wall shading, and fenestration performance, which invariably affects the amount of energy required for cooling (Lam et al., 2005). Kuhn et al. (2001), have stated that only a small amount of solar radiation incident on a building wall is transferred through openings. The average intensity of solar energy incident on a horizontal building plane is 1000W/m2 annually while that on a vertical wall plane facing Eastern and Western direction is 850 W/m^2. In the tropics, therefore, it is preferable to have windows facing towards the North and South directions to minimize the impact of solar radiation (Djamila et al., 2011). This study has also shown the importance of window wall ratio (WWR) in balancing between daylighting and cooling effects. A WWR of 25% is required as the optimum for achieving both lighting and cooling in office buildings (Nikpour et al., 2012; Zain-Ahmed et al., 2002). The need therefore to study the energy performance of existing buildings have become paramount, as it would lead to the building improvement and also an increase in the design of new buildings for better energy efficiency.

There is a high need for the provision of optimum environmental comfort conditions for office workers regarding solar irradiation, ventilation, and thermal comfort. However, meeting these essential needs of building occupants is synonymous to increase in energy consumption. The quest towards providing a comfortable environment to building occupants at reduced energy demand has led to the promotion of sustainable and green building design, application of energy harvested from renewable means and efficient heating, ventilation, and air-conditioning system (Anselm, 2006). This ingenuity has been adopted by different countries including Malaysia towards reducing natural fuel and the application of energy from renewable resources, to mitigate global warming and climate change (Begum et al., 2011). A reduction in energy demand in a building can be reduced through heat gain reduction. The decrease of heat gain through a building fabric can be achieved through external shading, window-wall area, glazing type, surface finish, shading coefficient (SC), solar heat gain coefficient (SHGC) etc (Lam et al., 2005).

The evaluation of a building in use through systematic analysis provides the avenue for identifying success in the design features that can be promoted for future use. External shading geometry on buildings has been found to contribute considerably to reducing energy consumption for cooling loads due to its shading behaviour. An external building shading can, therefore, be designed to achieve energy efficiency in multi-story office buildings (Dilshan R Ossen et al., 2005). Several buildings have been designed such that their exterior facades could enhance their thermal performance. Some of these buildings have Self-shaded facades and includes amongst others; the Energy Commission building (Diamond Building) in Putrajaya, Malaysia (Fig. 2), Bank of Israel in Jerusalem (Fig. 1a), and Bat Yam City Hall also in Israel (Fig. 1b). The above-mentioned building facades act as a shield to the sun not allowing it get into the building. Such strategies that was employed on these buildings reduces the amount of incident solar radiation thereby reducing the peak-cooling load of the buildings. Another example of a building having a self-shading façade is the Madrid's 'Distrito C' office building (Fig. 1c) whose façade was designed with protruding panels acting as sun visors, as well as, providing the building with a unique aesthetic character. The self-shading of the building is provided through its twisted form configuration that protects the building from direct solar heat gains.

An investigation carried out on Energy Commission building in Malaysia, have shown that the application of active energy sustaining design approaches are still under trial examination (Xin and Rao, 2012). In designing a building for energy efficiency, an important parameter to be considered is heat gain into the building (Malaysian Standard, 2007). The quantity of heat transmission from the outdoor to the indoor space of the building through the building fabric is called the overall thermal transfer value (OTTV) (Tzikopoulos et al., 2005). OTTV is therefore used as a basis for achieving optimum building fabric design towards reducing heat penetration through external walls. Therefore, to promote inclined wall self-shading strategies in the design of office building facades, an investigation of the self-shading scheme employed on the Diamond building is carried out to ascertain its effectiveness on heat gain and cooling load demand. The study is aimed at exploring the performance of inclined wall self-shading façades towards reducing heat gain and load for cooling. In determining the most efficient self-shading strategy, different models of an office space having the wall façade inclined at various self-shading projection (SSP) are modelled. The significance of this study is in providing an improvement of design databases, criteria, and control literature towards making of better-informed design decisions and having an understanding of the implications of design (Preiser, 2005).

2. Study area

Energy Commission building called "Diamond Building" as one of the Green rated office buildings in Malaysia has drawn the attention of many in recent times. This building is a remarkable edifice in the sense that, it showcases how efficient building design strategies can reduce energy demand as a means of realizing zero energy building. The Energy Commission building exhibits the potentials of sustainable green building initiatives, which is integrated with smart technology innovations to achieved energy efficiency.

The design of Diamond building is like a pyramid turned upside-down and had its top vertex buried underground. The building has eight (8) storeys with a deep floor plan. The building reinforced concrete slabs used for the roof and floors were designed with embedded elastic 22mm PERT cold water pipes, as a cooling storage system. It has a building façade that symbolizes a Diamond shape (Fig. 2). The choice of this form is to create a self-shading effect such that direct sun rays are eliminated from the building while allowing diffused daylight. The design strategies of the building are of energy performance, efficient water management, indoor environmental quality and sustainable building landscape. The building has a tilted façade that is extensively glazed whose configuration provides shading for the lower floors, prevents direct solar radiation on the façade, and also offers a smaller building footprint. The low E-glass used on the building façade walls is to reduce radiant heat infiltration. The building orientation follows the Sun path pattern to minimize the area that is impacted by direct sunlight. The tilted façade eliminated any

Fig. 1. Examples of some Selected Self-Shaded Buildings (a) Sketch of Bank of Israel, Jerusalem (b) Sketch of Bat Yam City Hall (c) Sketch of Madrid's 'Distrito C' Office Building, Spain.

Fig. 2. Exterior view of the case building. (Source: Field Photo).

requirement for external shading devices as it is self-shaded from the incidence of solar radiation and heat (the upper floors providing shade to the lower levels). The Diamond building has surrounding landscape as shown in Fig. 2 as an external obstruction but acting as barriers to heat gain into the building. Tall trees are lining the streetscape serving as shading/cooling to the building.

The Diamond Building derived 50% of its lighting from the natural daylighting, having a "Diamond Dome" on the rooftop as a crown made from marinated tempered glass for the skylight. On the building façade is an installation of low E-glazing of about 60% WWR that is reflective on the exterior, which allows daylighting and minimizes heat gain from the sun. All the exterior façade have split window design with internal light shelves to increase the illuminance level of natural light deeper into the office working space. According to Koay (2011), everything about the Diamond building and in the building, from the component materials, computers, and lighting systems are all sustainable and energy efficient. The building was designed to meet up with the criteria for energy efficient buildings having a building energy index (BEI) less than 135 kWh/m2 annually. The Diamond building operations consume just about one-third (1/3) of energy as compared to other office buildings in Malaysia, which has made it an award winner of 2012 ASEAN Energy Award in New building category (Leung & Mar 2013).

3. Methods

The experimental on-spot measurement was employed as a means of collecting environmental data in the case study building, located at Putrajaya, Malaysia. The field measurements were carried out seven days from 4th November to 16th December 2014. Malaysia peninsular is located along the equator and is characterized by a uniform temperature range and high relative humidity all through the year and a profuse rainfall. A look at the weather forecast of Putrajaya for seven days provided an average day-to-day temperature range of 25–33 °C. This study was carried out on the fourth floor of the case building, with a particular office space chosen as a location point for field measurement. The fourth

floor of the building is the only floor allowed by the facility manager to be accessible for any kind of study related to the building performance, to be carried out by any external researcher. It is worthy of note that the building inclined wall facades is at an angle that is same from the second floor to the last floor. The office space selected for the study has a west facing orientation. The equipment used for collecting data in the Diamond building is the HD35ED series data logger with an HD35AP base unit.

The HD35ED series instrument has built-in sensors that measure environmental variables such as air temperature, relative humidity, dew point, vapour pressure, mixing ratio, absolute humidity and wet bulb temperature. The HD35ED data logger can be connected to a personal computer (PC) through the HD35AP based unit and an installed HD35AP-S software which allows database access to recordings from the data loggers. The physical quantities acquired/measured through the data loggers can be viewed in real time on the PC screen. The outdoor measurement was carried out on the rooftop as the highest point of the building. Reflection at the rooftop is minimal as the roof is also constructed of green planting elements (Fig. 4d). The measurement units were set and configured by the base unit.

3.1. Field measurement

Field measurement in the test office room space (west facing orientation) was carried out from 7.00am to 5.00pm only on one particular day of the week consecutively for seven (7) weeks, from 4th November to 16th December 2014. The single day per week was due to certain restrictions on access to the case building. The Energy Commission building is allowed for any form of case study only on Tuesday each week. Fig. 3 shows the office room configuration and dimensions identifying locations for installation of the data logging instrument. The data measurement for this study was carried out in an open office room.

Based on the availability of instrument, only a single office room located on the 4th floor of the building was equipped with the measurement sensors with locations as shown in Fig. 3. The measured variable data from the logger were downloaded and transferred into Microsoft-Excel for further analysis. An average of the seven days measurement was computed as a representation of the daily office room condition from morning to evening. A series of experimental tests were conducted on seven (7) different days to investigate the heat gain performance of inclined wall self-shading strategy. Fig. 4 shows pictures of the field measurement carried out in the study office space. Also, the outdoor environmental variables were measured by placing another data logger on the rooftop which measured the same variables as the indoor (Fig. 4d).

3.2. IES-VE ApacheSim computer simulation

This study is conducted using the Integrated Environmental Solution - Virtual Environment (IES-VE) simulation software for Architects as a tool to investigate the effect of inclined wall self-shading strategy and heat gain in an office building in Malaysia. The IES-VE is an active building energy simulation software that has the capabilities of investigating
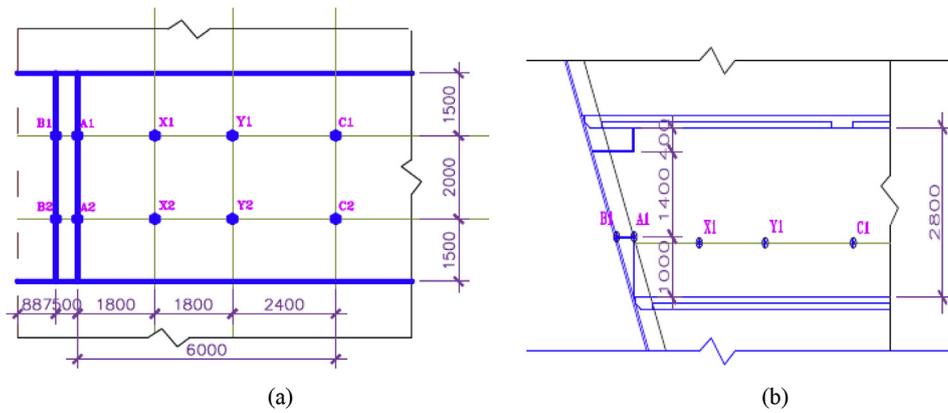
Fig. 3. The Case Building Office Space Geometry for on-spot Data Collection, (a) Plan; (b) Section. (All measurements are in millimetre).
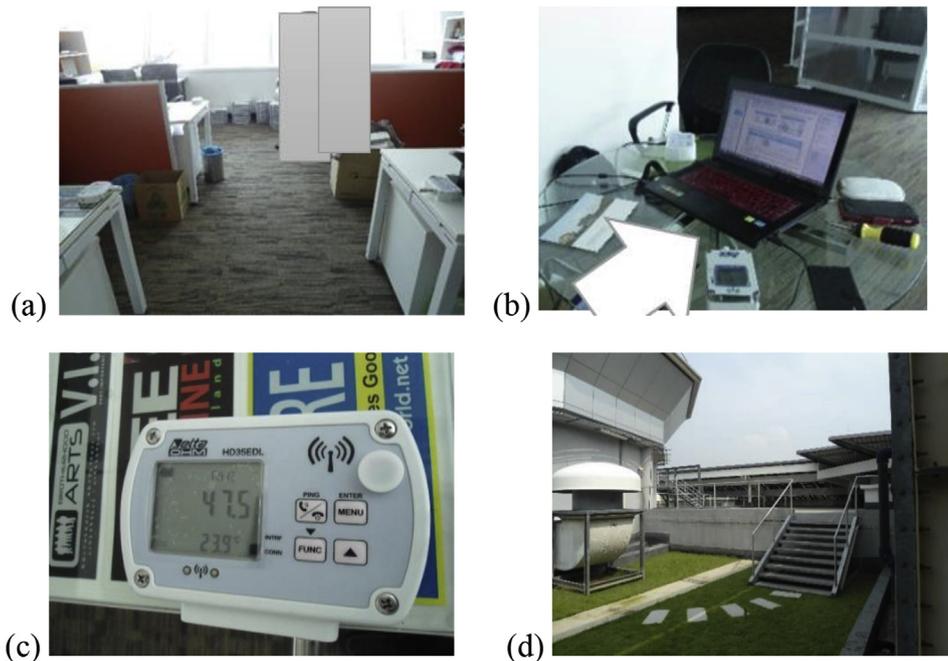

Fig. 4. Office room Space Selected for measurement and Datalogger locations (a) Selected Office Space; (b) HD35AP based unit; (c) HD35ED series data logger; (d) The Building Rooftop.

building performance either in retrospect or at the building early design stage. The IES-VE simulation tool was used as a commissioning tool in the design and construction process to validate and inform the design team on anticipated performance of the first zero-net energy retail store in the United States (US). This same simulation tool has also been employed in carrying out an extensive energy audit on 191 Main Street West Hamilton building, in Canada. This software consists of different programs of integrated design and analysis tools such as; ModelIT, ApacheSim, Radiance, MacroFlo, Computational Fluid Dynamics (CFD), etc., which has been found to have better accuracy than other computer simulation tools (D. R. Ossen, 2005).

A study conducted by Reeves et al. (2012) comparing the results of energy simulation results obtained using three different simulation tools inclusive of IES-VE revealed an inaccuracy in their prediction of actual building energy consumption. However, IES-VE seems to be the most accurate than the other two (Ecotect^{TM} and Green Building Studio). On the contrary, IES-VE simulation tool was validated in a study by Beever (2010) as a tool that provides accurate building performance data. Furthermore, the results of a study carried out by Chinnayelaku (2011)

using as well IES-VE simulation tool, have revealed that there was no any considerable statistical difference in the average values of both measured data and simulated results. Wong and Willand (2013) have also used the IES-VE simulation tool to predict the yearly operational energy demand on some selected commercial buildings. The simulation tool was able to provide an approximate model of complicated relationship, allowing a close to realistic modelling of the HVAC systems used in the studied buildings.

For this study, the ApacheSim simulation program is employed as the tool for analysis. ApacheSim is a self-motivated thermal simulation package which is based on carefully worked-out modelling of heat conduction in and out of indoor spaces. ApacheSim simulation provides a platform for comprehensive evaluation of a building and its systems, which also allows it for optimisation concerning comfort criteria and energy use. Using the IES-VE material library, the simulation model properties from wall and windows such as size, type, area, U-value, shading coefficient (SC), and WWR were extracted in line with the existing properties of the case study building earlier described in Section 2.
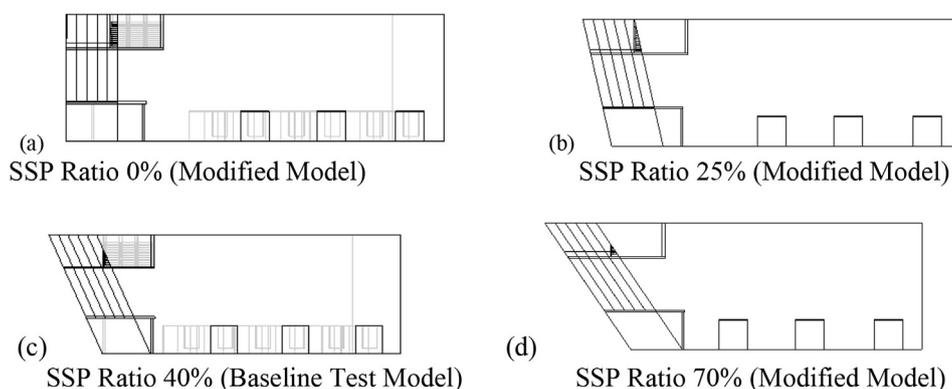
Fig. 5. Sketch of baseline Test model and different modified inclined wall Self-shading projection (SPP). (a) SSP Ratio 0% (Modified Model); (b) SSP Ratio 25% (Modified Model); (c) SSP Ratio 40% (Baseline Test Model); (d) SSP Ratio 70% (Modified Model).

3.3. Experiment condition and procedure for simulation

In an attempt to understand the influence of inclined wall self-shading strategy on improving heat gain in buildings, further simulation tests and analysis were conducted using different self-shading projection (SSP). The SSP is based on the ratio between the inclined wall shading projection and the vertical height of the building. The simulation tests on the trial baseline model and modified inclined wall self-shading strategy were carried out on four different design days. The parameters analysed from the simulated results are; air temperature, relative humidity, wet bulb temperature, dew point, the amount of heat gain through wall and windows, solar heat gain, and OTTV.

The room configuration and condition of the office space where field measurement was carried out was imitated as the model for simulation analysis. Only the side of the office room space having an inclined wall was modelled for analysis. Other surface properties of the room space were modelled according to the actual office space. The simulation study was carried out on four design days as from the hours of 7:00 am and 5:00 pm. Results from both field measurement and simulation were compared and analysed to determine the software accuracy. The validation of the simulation software is based on percentage difference computed as; a percentage of the ratio of the difference between simulated measurement to the field measurement and Pearson Correlation coefficient. The Simulation was carried out on annual thermal performance on the different models with variations in SSP as shown in Fig. 5 and Table 1. This simulation aims to establish the capacity of every simulated inclined wall strategy towards achieving thermal performance and cooling load reduction. The annual and daily averages of the performance variables of the different defined indices at four design-days were computed and compared.

3.4. The baseline model

A study of an office room space located on the fourth floor of the case building was conducted. The surface properties were based on the properties of the material components of the building. This case study office space was employed as the baseline model for simulation. Using the baseline model, different other angles of inclined wall self-shading were defined as shown in Table 1. Below. The external walls of the Diamond building are inclined at the same angle in all the four different facades. Therefore, the effect of the building self-shading is taken to be the same in all the offices at each floor level. Hence, the choice of single office space on level four of the office building for measurement and study. The building glazing has a solar heat gain coefficient (SHGC) of about 0.37 with an emmisivity of 0.16, and a shading coefficient of 43%, which reduces greatly the direct influx of solar heat gain on the East/West orientation. The glazing also has a visual light transmittance of about 52% and a U-value of 0.072Wh/m²K. On the other hand, the

Diamond building has a shading coefficient (SC) of 0.53 for the north and south orientation, visual transmittance of 55.9%, solar heat gain coefficient (SHGC) of 0.46, and a U-value of 0.956 W/m²K. It has a window wall ratio (WWR) of about 60% (Nikpour et al., 2012). The internal wall properties of the building includes the usage of light shelf mirrors with painted window sill, white ceiling and without internal partitions, and no suspended ceilings.

The building appeared to be fully glazed, however, it is cladded with metal at the first one meter of each floor. This is as a result of the fact that, the lower section of the building does not have any impact in terms of thermal performance and daylighting.

3.5. Variation in self-shading projection (SSP)

The baseline model has a total floor height of 3200 mm and a shading projection of 1500 mm inclined at an angular projection of 65°. The self-shading projection (SSP) is therefore calculated as the percentage of a ratio between the shading projections of the inclined wall to the total floor height. The modified self-shading projection is derived by both increasing and decreasing the inclined wall angle of the baseline model as shown in Fig. 5 and Table 1, to determine the performance of inclined wall self-shading façades towards reducing heat gain and load for cooling.

4. Results and discussion

4.1. Field measurement

The variations in measured environmental variables as recorded within the selected office space of the case study building shown in Table 2. These measurements were taken at the height of 0.8m above the floor level. The outdoor environmental variables were measured at the rooftop of the building. The roof is an insulated concrete green roof that minimises heat absorption, as well as, serving as a base for water harvesting tanks and solar panels installations (Fig. 4d.). The outdoor measured variables at the rooftop characterise the instantaneous surrounding environmental condition essential for this study. An average outdoor air temperature ranging from 35.4 °C to -37.2 °C was recorded simultaneously with the indoor office space measurement. Fig. 6b shows the outdoor temperature variation which reaches a maximum peak of

Table 1
Self-shading projection (SSP) ratio used (Building height = 3.2m).

SSP (%)	Projection (m)	Height (m)	Inclined Angle
0	0	3.2	90
25	0.8	3.2	75
45	1.5	3.2	65
70	2.25	3.3	55

SSP = Shading Projection/Building height × 100.

Table 2
Mean measured environmental variables at selected points in the office room space.

Measurement location	Temperature (°C)	Relative humidity (%)	Wet bulb temperature (°C)
B1	25.4	51.1	18
A1	25.2	58	19
X1	23.5	49.2	16.6
Y1	23.2	48.5	16.2
C1	24.6	48.6	17.5
Outdoor Average	38.0	36.7	25.4
Indoor Average	24.4	51.1	17.5

36.5 °C at about 12:30 pm. As shown in Fig. 6a, the indoor air temperature was about 12–13.6 °C below the outdoor temperature as measured simultaneously. The average outdoor air temperature recorded for the location 36.2 °C, while the average indoor air temperature was 23.4 °C. Despite the fact that the office space area is air-conditioned, the slight variation in the indoor air temperature may be as a result of the difference in outdoor temperature and also a time of measurement.

The average relative humidity recorded at the office location was within the normal range (Fig. 6c). The relative humidity ranged between 48 and 51%, while the wet bulb temperature ranged between 16.4-16.9 °C (Fig. 6d). The difference between the mean outdoor wet bulb temperatures (24.9 °C) recorded at the rooftop, and the mean indoor wet bulb temperature was approximately 8 °C.

4.2. ApacheSim simulation validation

The IES-VE ApachedSim simulation tool was validated based on the outdoor environmental condition. Fig. 7 shows that the simulated results of air temperature and wet bulb temperature were consistently below the field measurement values. The highest variance between the measured outdoor temperature and the simulated temperature is about 49.2%, while the maximum variation for the wet bulb temperature is approximately 8.4%. On the other hand, the simulated results of the outdoor dew point and relative humidity were consistently higher than the measured results, having most top differences of about 12.1% and 55.7% respectively.

A comparison was also made by computing the percentage difference between the simulated results and the field measurement. Tables 3 and 4 showed that the external air temperature and relative humidity have average percentage differences in their simulated and measured results which were above the acceptable range of between 15%–20%. This might be as a consequence of the limitation of the modelling to imitate the real environmental solution. The percentage difference in the simulated and measured results for dew point and wet bulb temperature was consistently lower than the minimum acceptable limit of 15%. The results of the dew point and wet bulb temperature, therefore, recorded identical performance results.

A statistical Pearson correlation was calculated for the results of the measured and simulated environmental variables as shown in Tables 3 and 4. The statistical analysis revealed a significant relationship between the simulated and measured results of the environmental variables of consideration, all having a Pearson correlation value of not less than 0.70, except for air temperature (0.56). However, the Pearson correlation between the measured and simulated result of the air temperature is slightly higher than 0.50, which can be considered acceptable. The Pearson correlation between the simulated results and measured results for the wet bulb temperature was high as 0.88. This statistical result is a justification that ApacheSim-based simulation software is capable of precisely forecast environmental condition. The validation of field measurements has pointed out excellent reliability of the ApacheSim simulation model, with the aim to provide estimates of the heat gain behaviour of inclined self-shaded wall strategy. Hence, its adoption for the simulation of the defined models for heat gain performance
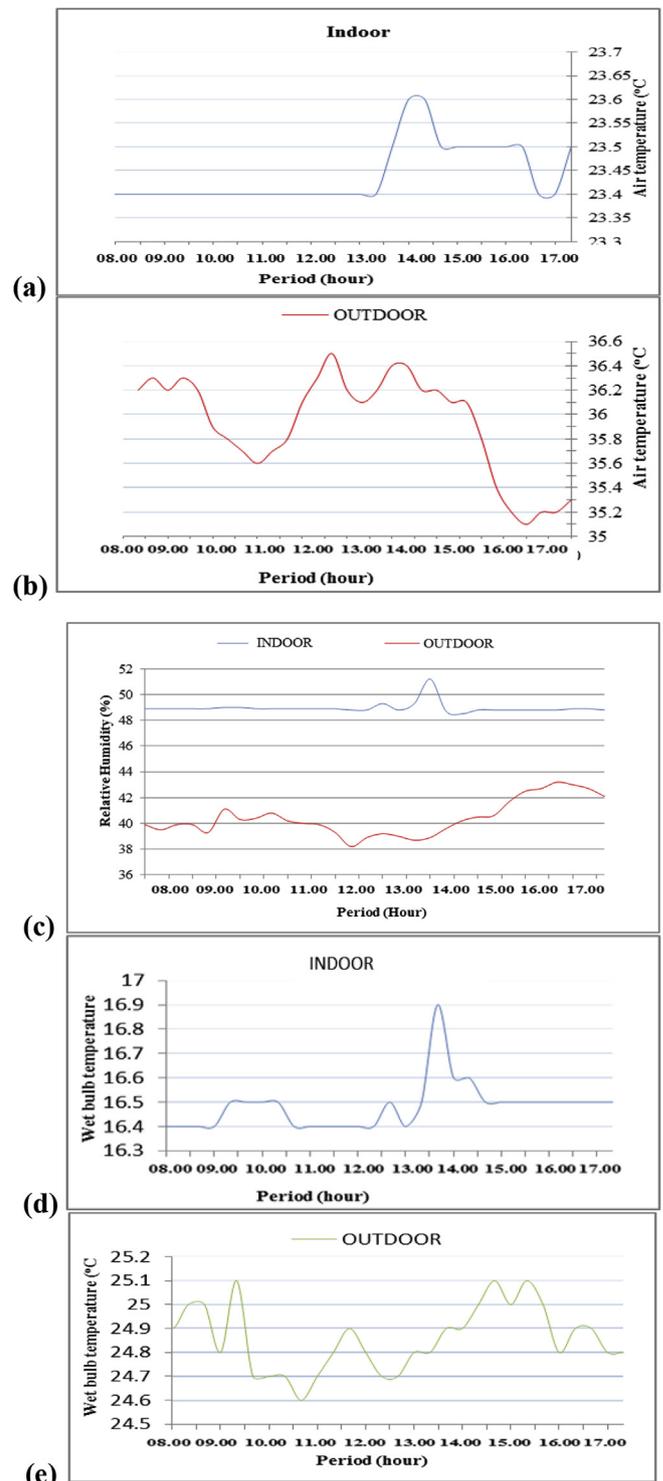
Fig. 6. Variations of Measured indoor and outdoor Environmental Variables (a) Air Temperature (Indoor) (b) Air Temperature (Outdoor) (c) Relative Humidity; (d) Wet Bulb Temperature (Indoor) (e) Wet Bulb Temperature (Outdoor).

measurement.

4.3. Heat gain analysis

Under the same condition, different self-shading projection (SSP) has a different capacity of allowing heat penetration into a building space as a result of their differences in their characteristics. The analysis of heat gain performance of the self-shading models as presented in this section
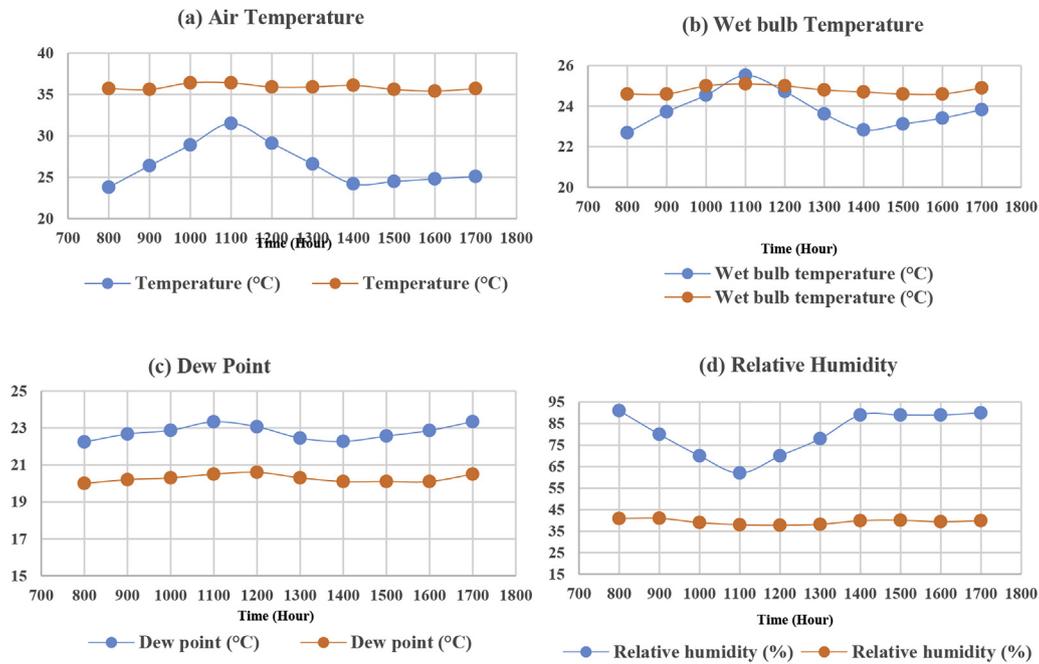
Fig. 7. Comparison of Measured and Simulated Environmental Variables. (a) Air temperature; (b) Wet bulb temperature; (c) Dew point; (d) Relative humidity.

Table 3
Percentage difference and correlation analysis between measured and simulated air temperature and wet bulb temperature.

Time	Temperature (°C)				Wet bulb temperature (°C)			
	Simulated	Measured	Percentage Difference	Pearson Correlation	Simulated	Measured	Percentage Difference	Pearson Correlation
7:00	22.7	25.7	11.7	0.56	22.72	24.5	7.3	0.90
8:00	23.8	26.7	10.9		22.7	24.6	7.7	
9:00	26.4	28.6	7.7		23.7	24.6	3.7	
10:00	28.9	35.4	18.4		24.5	25	2.0	
11:00	31.5	35.6	11.5		25.5	25.1	1.6	
12:00	29.1	35.9	18.9		24.7	25	1.2	
13:00	26.6	35.9	25.9		23.6	24.8	4.8	
14:00	24.2	31.4	22.9		22.8	24.7	7.7	
15:00	24.5	34.4	28.8		23.1	24.6	6.1	
16:00	24.8	36.1	31.3		23.4	24.6	4.9	
17:00	25.1	36.7	31.6		23.8	24.9	4.4	

Table 4
Percentage difference and correlation analysis between measured and simulated dew point and relative humidity.

Time	Dewpoint (°C)				Relative humidity (%)			
	Simulated	Measured	Percentage Difference	Pearson Correlation	Simulated	Measured	Percentage Difference	Pearson Correlation
7:00	22.32	20.1	9.4	0.84	91	42.2	44.6	0.74
8:00	22.2	20	11.0		91	40.9	55.1	
9:00	22.7	20.2	12.4		80	41	48.8	
10:00	22.9	20.3	12.8		70	39	44.3	
11:00	23.3	20.5	13.7		62	38	38.7	
12:00	23.1	20.6	12.1		70	37.8	46	
13:00	22.5	20.3	10.8		78	38.2	51	
14:00	22.3	20.1	10.9		89	39.9	55.2	
15:00	22.6	20.1	12.4		89	40.1	54.9	
16:00	22.9	20.1	13.9		89	39.4	55.7	
17:00	23.3	20.5	13.7		90	39.9	55.7	

is based on the quantity of heat gain through the defined self-shading projection, and the overall thermal transfer value (OTTV) recorded from the simulated results.

The performance of the indoor environmental condition of the study office space was analyzed in comparison with other modifications to the self-shading projection (SSP). The ApacheSim simulation of the existing baseline model (SSP-45) and the different modifications to the building self-shading façade (SSP-0, SSP-25, and SSP-70) were carried out. All the test cases are shown in Fig. 5, while Table 5 shows the annual solar shading and insulation on the different defined models. SSP-45 and SSP-70 received solar heat radiation of not more than 311.09 kWh/m2 annually on their wall surfaces. The lower the inclined wall self-shading projection, the higher the solar radiation the wall surface received, as SSP-0 received the highest solar radiation of over 800 kWh/m2.

Table 5
Annual solar shading and insolation for different self-shading projection.

Self-shading projection (SSP - %)	Wall Surfaces (kWh/m^2)
0	806.17–956.03
25	685.19–859.24
50	0.00–311.09
70	0.00–311.09

Table 6 indicates the heat gain performance results of the existing baseline model and modified self-shading projection (SSP) at four different design days. The baseline model (SSP-45), as well as the inclined wall self-shading modifications (SSP-70), did not receive any amount of heat penetration through the inclined walls in all the for design days. Table 6 also reveals that SSP-45 and SSP-70 did not gain any solar heat through the window glazing.

The inclined wall strategy having a self-shading projection (SSP-70) received the highest amount of heat conduction through the window glazing in all the four design days ranging from 0.20kW on 21 December to 0.34kW on 21 June. The least conduction through the window glazing was recorded on the baseline model (SSP-45) ranging from 0.17kW also on 21 December to 0.30kW on 21 June. Heat conduction through window glazing recorded the least on 21 December in all four models and even highest on 21 June. Heat conduction through wall received the highest on the conventional wall model (SSP-0) ranging from 0.18kW on 21 December to 0.24kW on 22 March. Also from the simulated results, there is no significant difference between the heat conduction through wall and window glazing in all four design days for the modified models SSP-0 and SSP-25, while there is a significant difference in both baseline model SSP-45 and the modified model SSP-70, which recorded a zero heat gain through the wall. These results are an indication that having inclined wall self-shading strategy can moderate heat penetration and gains into a building space as also opined by Chia (2008).

The overall thermal transfer value (OTTV) for all models on four design days is also shown in Table 6. The SSP-0 received the highest OTTV of 1.07kW on 22 March while the existing baseline model SSP-45 received the least OTTV of 0.17kW on 21 December. There is a consistency in the difference in the range of OTTV for the different self-shading projections, and for the various design days, which is 0.19kW, 0.20kW, 0.13kW, and 0.15kW respectively for SSP-0, SSP-25, SSP-45, and SSP-70. The least range difference for the four design days was recorded on SSP-45 (baseline model). The rate of heat transfer into the office space having an inclined wall self-shading projection (SSP-45) is significantly reduced as compared to SSP-0 and SSP-25. As much as the OTTV for SSP-70 is also low, the baseline model (SSP-45) exhibited a better performance regarding heat transfer.

Table 6
Daily average heat gain analysis for the different SSP on four design days.

Heat Gain	SPP	Design days			
		22-Mar	21-Jun	21-Sep	21-Dec
Heat Conduction through Wall (kW)	0	0.24	0.22	0.22	0.18
	25	0.22	0.21	0.20	0.16
	45	0.00	0.00	0.00	0.00
	70	0.00	0.00	0.00	0.00
Heat Conduction through Window Glazing (kW)	0	0.23	0.32	0.22	0.18
	25	0.25	0.34	0.24	0.20
	45	0.20	0.30	0.21	0.17
	70	0.27	0.35	0.25	0.20
Solar Heat Gain through Window (kW)	0	0.60	0.52	0.57	0.53
	25	0.55	0.49	0.53	0.48
	45	0.00	0.00	0.00	0.00
	70	0.00	0.00	0.00	0.00
Overall Thermal Transfer Value (OTTV) -(kW)	0	1.07	1.06	1.01	0.88
	25	1.02	1.04	0.97	0.84
	45	0.20	0.30	0.21	0.17
	70	0.27	0.35	0.25	0.20

4.4. Heat gain performance of various self-shading projection (SSP)

Fig. 8 provides an overview of the mean heat gain through window and wall, solar heat gain penetration through the window and the overall thermal transfer value (OTTV) for all the self-shading projections. Heat gain through the window was lowest in the test baseline model (SSP-45) and highest in SSP-0 between the hours of 9.00 and 16.00. The maximum heat conduction through window glazing recorded for SSP-0 was 0.47 kW at 14.05 hrs, while the least for SSP-45 was 0.08 kW at 7.05 hrs.

Heat conduction through window glazing was higher for SSP-45 and SSP-70 than for SSP-0 and SSP-25 between hours of 7.00 and 9.00. The results showed that there was no heat conduction through the wall, as well as, solar heat gain through the window for SSP-45 and SSP-70 as the recorded heat gain is zero. This is an indication that inclined walls have the capabilities of eliminating direct solar heat gain into a building space. SSP-0 on the other hand, recorded the highest heat conduction passing through the wall and solar heat gains within the period under consideration. This result reveals that self-shaded buildings have a way of reducing heat gain both through walls and windows. According to Capeluto (2003), self-shading strategy in buildings provides a better solution towards energy use in buildings. The result of this study is therefore in line with Capeluto assertion. It is also evident that an increased in self-shading projection (SSP) resulted in a reduction in heat gain, however, the test baseline model (SSP-45) even though with a lower self-shading projection have better performance than SSP-70 in reducing heat gain.

The results of the OTTV revealed a similar trend for SSP-0 and SSP-25 between the hours of 7.05 and 13.05. A negative OTTV was recorded for SSP-0 and SSP-25 at the early hours before 7.30, which increased with gains in time until about 14.0 hrs when the OTTV started declining. There was a heat reduction difference of about 0.39kW between the baseline model (SSP-45) and the conventional wall model (SSP-0). There was no much difference between the OTTV for SSP-45 and SSP-70 which were both significantly lower than the OTTV for SSP-0 and SSP-25. A low OTTV in buildings is responsible for reduced energy consumption (Li et al., 2002). The baseline model (SSP-45) which represent the Energy Commission Diamond building has been considered as a building having low energy consumption as noted by Bux and Othman (2014). This is evident in the results of the OTTV (Fig. 8d) where the SSP-45 as the baseline model exhibited heat gain minimisation due to its self-shading wall strategy, which in return, is therefore responsible for the reduction in energy consumption.

As seen from this study, the distinct form of the Energy Commission Diamond building having an inclined wall façade at an angle of 65° to the horizontal plane as an ideal passive design strategy, have been proven to achieve sustainable energy efficiency (Koay, 2011; Leung & Mar, 2013; Shari and Soebarto, 2012; Suruhanjaya Tenaga, 2011; Xin and Rao, 2012). The baseline model (SSP-45) in this study recorded the highest heat gain reduction from the simulated results.

5. Conclusion

This study focuses on the heat gain performance of inclined wall self-shading. The primary objective of this paper is to examine the current state of thermal performance of the inclined wall self-shading strategy of Energy Commission Building (Diamond Building) located in Putrajaya, Malaysia, and to also determine the optimum self-shading projection for efficient heat gain reduction. Both field measurement and simulations were carried out and analysed to quantify the effect of inclined wall self-shading strategy towards reducing heat gain and energy consumption for cooling.

Heat conduction through wall and window as well as, solar heat gain were estimated for a test baseline model and other modification to inclined wall self-shading projection. Also, in trying to ascertain the best-inclined wall angle with the least level of heat penetration, the amount of OTTV was calculated for the various self-shading projections. The
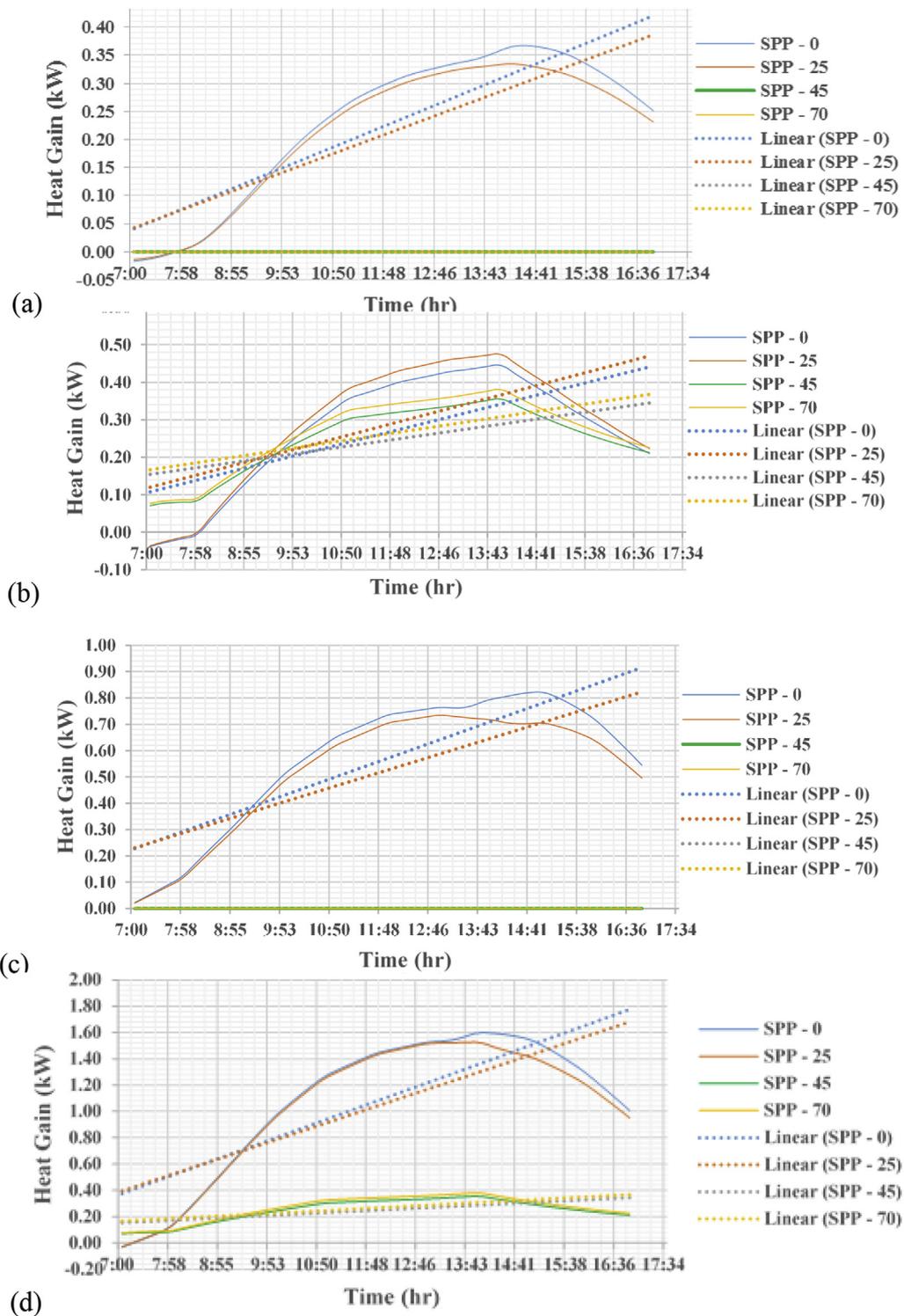
Fig. 8. Variation in Heat Gain with different Self-shading projection. (a) Heat conduction through walls; (b) Heat conduction through Window glazing; (c) Solar Heat gain through window; (d) Overall thermal transfer value (OTTV).

finding from the results can be summarised as follows:

1. There is a relationship between heat gains into a building space and the self-shading projection, as heat gain tends to reduce with increased SSP.
2. A self-shading projection of 45° (SSP-45) and above received a zero heat conduction through walls and zero solar heat gain through windows.

3. OTTV is minimal in the baseline model (SSP-45) as compared to other self-shading projections. SSP-45 happens to be the test baseline model (Energy Commission building), which has the least possible level of heat gain during working hours. This can be seen as the best self-shading projection to be adopted for inclined wall strategy.
4. The design of self-shading using an optimum SSP-45 inclined wall strategy at an angle of 65° to the horizontal plane, as evident in the

Diamond building has exhibited the best performance regarding reduction in heat gain and energy demand for cooling.

Inclined wall self-shading strategy has shown to be of considerable impact on reducing direct solar gains and heat conduction into a building space. This study has found out that, the optimum inclination angle of self-shading for efficient heat gain reduction is based on a 45% self-shading projection. The application of inclined wall self-shading strategy in buildings would, therefore, bring about a decrease in the amount of OTTV, which would invariably reduce energy consumption for cooling. Inclined wall self-shading principle can, thus, be employed by design Architects towards energy-efficient and green buildings delivery.

Declarations

Author contribution statement

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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