Mechanical cooling energy reduction for commercial buildings in hot climates: Effective use of external solar shading incorporating effects on daylight contribution

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Abstract

This paper investigates the effectiveness of multiple external shading devices and identifies the most effective fixed external shading configurations for commercial building types in hot climates. Daylight contribution is also analysed in detail in order to monitor the daylighting factor reduction including uniformity for each shading configuration. Existing dynamic thermal modeling software is used to completing analysis on a theoretical open office plan building. Simulation results indicate that multiple angled external shading is the most effective solution for commercial buildings in hot climates. The calculated diurnal cooling load reduction for East, South and West elevations are 46.20%, 41.16% and 46.53% respectively. Furthermore, daytime cooling load (kW) reduction is reduced by 17.80% using the optimum solution. All dynamic thermal simulations are compared against a base case to clearly show possible cooling energy reduction (MWh) and carbon dioxide emissions (CO_2) associated with cooling system for single storey open office building.

Keywords: External Fixed Solar Shading; Daylighting; Energy Consumption; Carbon Dioxide Production.

1. Introduction

In hot climates where local external air temperature exceeds 25°C, large quantities of electrical energy are used to cool indoor environments, maintaining internal comfort temperatures. Overheating is particularly important problem for commercial buildings as high internal temperatures have a dramatic effect on a person/s productivity and wellbeing. To overcome this issue, mechanical cooling is provided to effectively remove heat gains from the space/s. The size of these cooling systems depends on factors such as infiltrated heat gain, external air temperatures; people heat gains (sensible and latent), equipment heat gains and solar gains via glazing.

Low carbon commercial buildings are now designed to encompass hybrid (mixed mode) operation where natural ventilation and passive systems are combined together. To minimise solar gains via glazing, fixed external solar shading is used as an effective passive system since no control energy is required. Once correctly placed, significant amounts of solar gains can be absorbed/deflected. However the daylighting aspects of the shading devices need to be considered since substantial reduction in the indoor illuminance levels requires more artificial lighting hence increasing building energy consumption.

As described by Littlefair (1999), external fixed solar shading devices are defined as overhangs, canopies, light shelves, shutters, vertical fins, roller blinds, egg create baffles and local tree and vegetation. There are many types and methods of external shading available from fixed horizontal type to full facade steel mesh. Research completed by Tzempelikos & Athienitis (2006) on exterior roller type shades shows a 36% reduction in annual cooling energy consumption. Furthermore, when reviewing effective types of blinds, Wienold et al (2011) discovered that a combination of External VB silver (external mounted) and internal rollo blind had the most impact by reducing annual energy consumption by approximately 29% when compared with the basecase.

With reference to louvre depth, a study completed by Walliman & Resalati (2011) on a commercial building in Shiraz, South of Iran, solar shading devices using 20cm horizontal louvres provided a 32% saving in reduction of cooling load.

For daylighting performance in spaces, using horizontal and vertical shading devices, Alzoubi & Al-Zoubi (2009) reported that surplus artificial light energy is higher for horizontal angled type shading (45°) ($47W/M^2$) compared to base case model ($26W/M^2$) indicating a 55% increase when external shading is used. This analysis was completed for south facing windows only.

For optimum angles with regards to heat deflection and daylight maximisation, Lieb (2001) states that; *'The sun shading provides either a complete screening of an area behind it or, in the cases of louvres, it may be in a so called 'cut off' position. This is the angle of the louvres at which the blind allows no direct radiation to penetrate it'.* Lieb (2001) continues to explain that the basis of design and installation is perpendicular incidence of light

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and the cut off angle is usually 45°. Louvres at steeper angles will provide a greater degree of shading but will reduce daylighting contribution proportionately.

However further work is required to determine the impact of common types of external fixed solar shading devices in hot climates, in particular, commercial type buildings.

The aim of this work is to investigate the effectiveness of the solar shading for commercial buildings in hot climates in terms of solar heat gain reduction and daylighting maximisation. The aim is realised by the following three objectives:

1. Dynamic thermal modelling simulation for a single storey exemplar theoretical commercial building located in a hot climate. Four types of external fixed solar shades and one type of internal blind is compared and analysed.
2. Determine the most effective method of fixed external solar shading in terms of cooling energy reduction and daylight factor.
3. Using most effective method, calculate cooling energy consumption and associated carbon dioxide production from an electrically powered mechanical cooling system.

2. Research Methodology

A theoretical commercial building model was created for five methods of solar shading. Building simulations were completed for four different external fixed solar shading methods and one internal blind for East, South and West windows. Model analysis determined the most effective form of fixed external shading using daytime dynamic analysis (stage 1) and stage 2 will analyse building energy reduction, using ideal shading solution discovered in stage 1.

The climate selected is detailed in Table 1 below which identifies the maximum temperature and minimum temperatures based on the height above sea level (World Meteorological Organisation, 2012).

Location	Altitude (m) Above Sea Level	Max. Temp. (°C)	Min. Temp. (°C)
Aswan, Egypt	194	41.1	26

Table 1- Climate Data for Hot Countries

For the peak diurnal analysis, 29th July has been selected as records show this is currently the hottest day of the year for this area. Climate data will be design summer year (DSY) in the building simulations.

The metrics (SI Units) used in this analysis are: cooling energy consumption (MWh), carbon dioxide production ($kgCO_2$/hour & $KgCO_2$/Annum) and average daylight factor (DF = (Ei / Eo) x 100%) where, Ei = illuminance due to daylight at a point on the indoors working plane units (Lux), Eo = simultaneous outdoor illuminance on a horizontal plane from an unobstructed hemisphere of overcast sky (Lux).

The building has been created and simulated using IES VE 6.4.0.10 incorporating finite differencing calculation methods. In particular, dynamic diurnal solar gains and annual energy consumption are calculated using Suncast and Apache. The simulation time is 1st January to 31st December. For daylighting calculations, FlucDL is used for 29th July at 1200 hours. For artificial lighting calculations Dialux software version 4.10 was used to determine light levels and energy consumption.

The simulations are broken down into two stages:

- Stage 1- Analysis to determine optimum fixed external shading solution for the hot climates selected. Solar gains and daylighting impacts to the space for each type of shading device for each elevation (E, S & W). For Northern hemispheres, North facing walls are not included as part of this study as solar gains are minimal compared to stated orientations.
- Stage 2- Whole building analysis with windows and optimum shading devices added to East, South and West walls to determine annual cooling energy consumption (electrical), associated carbon dioxide emissions and overall impact on daylighting to space.

3. Exemplar Model Design Criteria

A single storey theoretical model 20x20m was created with a floor to ceiling height of 4.5m, designed as an open plan office. One elevation has three 4m x 2m windows and the north elevation has two wooden doors only. The construction is medium/light weight type.

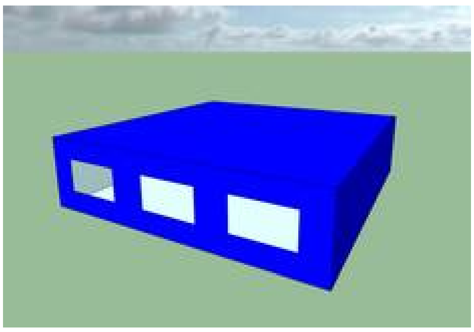

Figure 1- Model of Single Storey Commercial Building under study

The base case design criterion is taken from United Kingdom Building Regulations (HM Government, 2010), British Standards and BSRIA Guidelines (BSRIA 14, 2003) relevant to each type of building. Building parameters are listed in Table 2 below:

Type	Description
External Walls	Outer Leaf Brickwork, Dense EPS slab Insulation, Concrete Block (medium density), Gypsum Plasterboard and Gypsum plastering- U value of 0.36W/m^2 K
Roof	Stone chippings, Felt/Bitumen Layers, Cast Concrete, Glass Fibre Quilt, Air Cavity and ceiling tiles finish Ceiling- U Value of 0.25W/m^2 K
Floor	Standard Ground, Brickwork (Hardcore), Cast Concrete, Dense ESP Slab Insulation (Like Styrofoam), chipboard and synthetic carpet- U Value of 0.25 W/m^2 K
Glazing	Low e Double glazing 6mm+6mm Pilkington K glass- U Value of 1.97W/m^2 K
Doors	Wooden Doors (Pine) - U Value of 2.20 W/m^2 K
Air Permeability	0.25 Air Changes Per Hour
Ventilation	10 Litres/Second/Person.
Commercial building mechanical cooling set point for Indoor Conditions (Thermal Comfort)	23^{o}C
Internal heat gains are based on occupancy and lighting heat gains only	150W per person (combination of Sensible (90W) & Latent (60W)) and 12W/m^2 respectively (as a minimum).
Total occupancy	Allow 12m^2/person in usable space, 400m^2/12m^2= 34 people.
Occupancy Pattern	0800-1800. 50% occupancy 1200-1400.
Mechanical Cooling Fuel Source	Electrical
Artificial Lighting Design	56No. Thorn Lighting Line XS Tech 2x35W Suspended direct/indirect luminaires- 516lux (AL_1) at 0.85m above finished floor level. uniformity 68.5%. Total continuous Power Demand is 4.2kW including electronic ballast losses. Specific connected load: 10.50W/M^2=2.05W/M^2/100lux (Dialux Output). The luminaire quantity array is 8 x 7.

Table 2- Building Parameters

The mechanisms used to validate the base case were to compare simulated output results against bench mark values in the above standards, which were verified by the authors.

4. Selected Fixed External Solar Shading

The shading selected for this analysis is opaque, no thermal conductivity (0W/m^2k) and an overhang depth of 300mm (O_D) for all scenarios. The selected shading device types below (Figure 2) are selected below based upon Windows & Daylighting (2013) common configurations.

Figure 2 also shows the relationship between the overhand depth (O_D) and window height (W_h), where the greater O_D the greater the reduction of solar gains. The shading devices are angled at a maximum of 45 degree (cut off angle) and the effective window height (Ewh) is maximised (CIBSE, 2006).

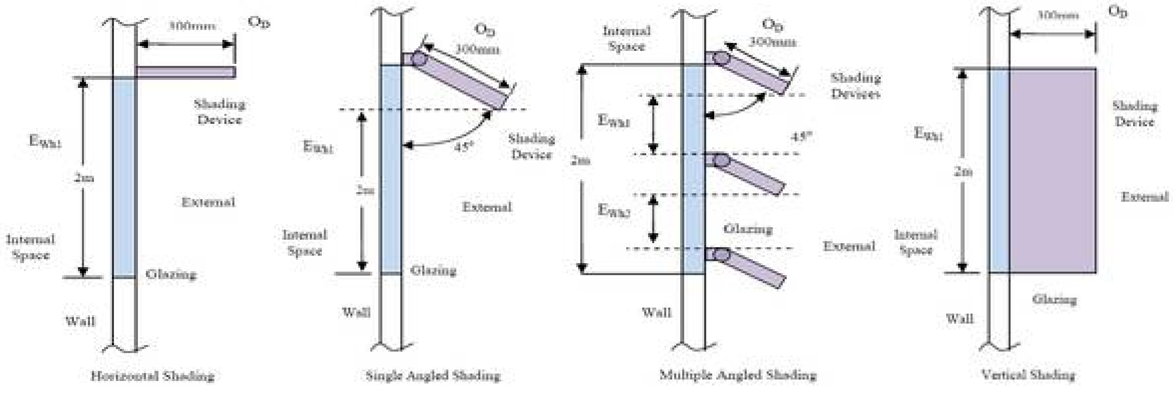

Figure 2- Common Forms of External Solar Shades

5. Stage 1 Simulation- Effectiveness External Fixed Solar Shading Devices

5.1 Diurnal Solar Loads

Dynamic simulations were completed for each elevation to determine thermal performance for each type of solar shading device. Effectiveness is defined as the total reduction of solar heat gain admittance into the office space via windows. Figures 3 to 8 show the daytime solar heat gains (kW) for each type of shading and elevation. Each simulation is completed with glazing provided to one elevation only. The model wall orientation is then changed to desired bearing (S, E or W). All outputs are compared against a base case model (no shading).

For optimum shading analysis, Figures 4, 6 and 8 compare base case, effects of internal blinds which are closed 50% of daylight hours and optimum shading solution. These are calculated for a 24 hour period with a 10 day solar gain lead in. The calculation time step is 10mins. All calculations are based on McAdams external convection model.

Figure 3 below shows solar heat gain effects on the South facing windows for each external shading case with the base case indicating the maximum amount of gain for a daily period. The results of this show that horizontal and angled have similar performance (angled giving greater reduction), vertical shading indicates limited effectiveness, due to lack of shading at higher solar azimuths and multi-angled shading type being the most effective, providing the greatest reduction.

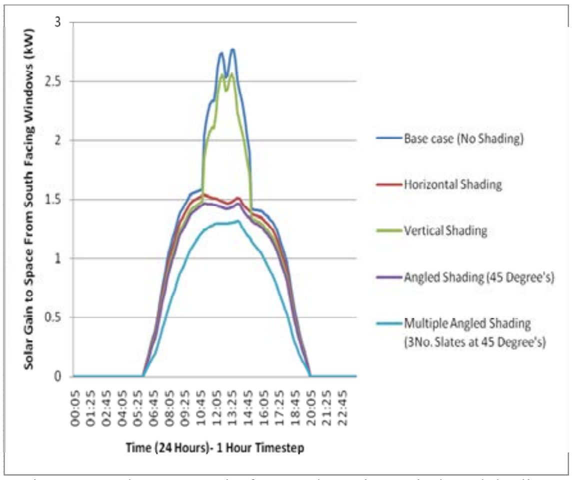

Figure 3- Solar Heat Gain for South Facing Windows/Shading

Figure 4 compares the most effective form of external shading (multi-angled), base case and base case with blinds closed 50% for daylight hours following occupancy profile. The graph shows the blinds having a significant impact during occupied hours. This is benefited by the external shading device as this provides a continued reduction over the daytime period where unoccupied hours can have higher levels of heat gain (peak periods).

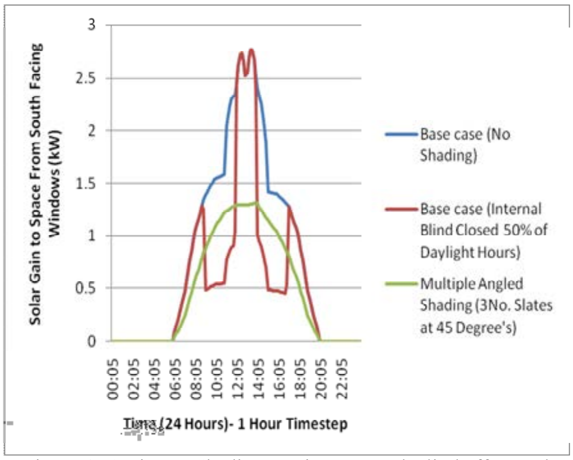

Figure 4- Optimum Shading Device, Internal Blind effect and Basecase Solar Heat Gain for South Facing Windows/Shading

Figure 5 shows identical analysis has been completed for East facing windows showing the multi-angled shading solution being the most effective. Figure 6 shows the external shading being more effective than internal blinds when comparing to Figure 4.

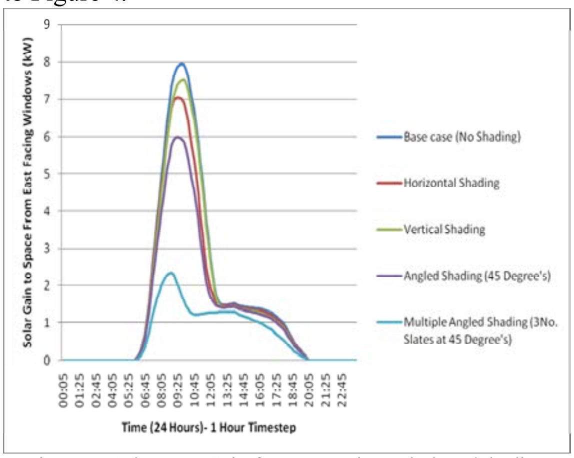

Figure 5- Solar Heat Gain for East Facing Windows/Shading

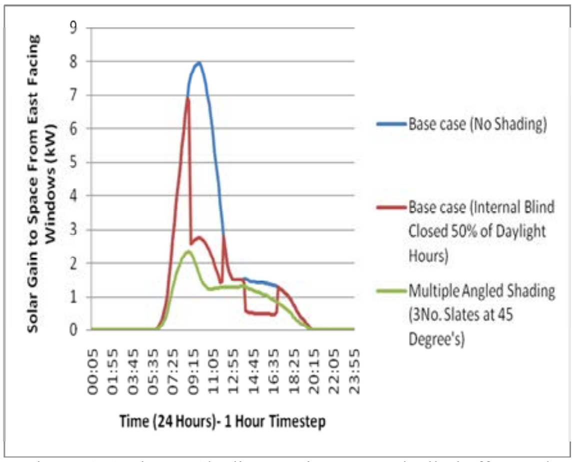

Figure 6- Optimum Shading Device, Internal Blind effect and Basecase Solar Heat Gain for East Facing Window/Shading

For West facing windows, the multi-angled solution provides the most effective solar gain reduction as shown in Figure 7.

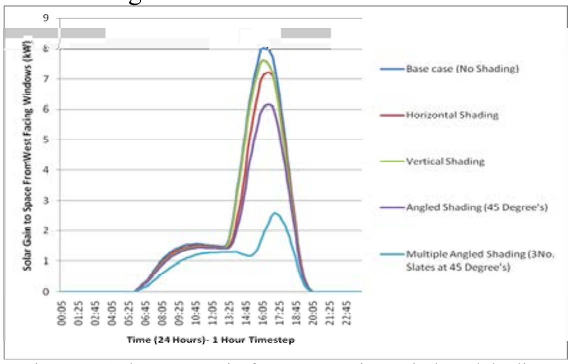

Figure 7- Solar Heat Gain for West Facing Windows/Shading

When comparing Figures 5 and 7, plotted results show that horizontal and angled external shading device on the East wall performs better than on the West wall as graph peaks show greater magnitude. Figure 8 shows a similar outcome to Figure 6 (East) where external solar shading performs better than internal blinds. When comparing all elevations (Figures 4, 6 & 8), the external solar shade for the East wall has the best performance for energy reduction, West glazing second and South glazing third. This is quantified by slightly higher heat gains to the West elevantion and the graph peaks show a slight increase in magnitude.

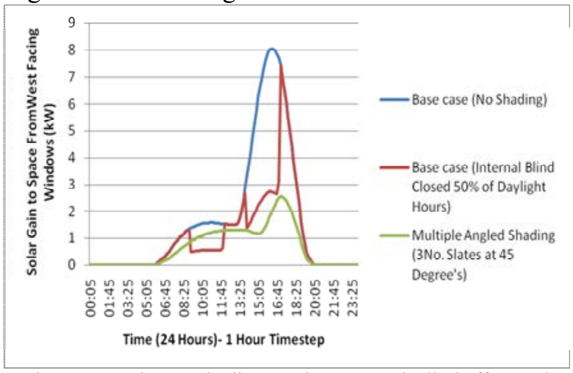

Figure 8- Optimum Shading Device, Internal Blind effect and Basecase Solar Heat Gain for West Facing Window/Shading

5.2 Diurnal Daylighting Effects

Daylighting calculations have been completed for each type of solar shading using CIE clear skys weather data and results are shown in Table 3 below. Table 3 has been created to provide a direct comparison for all forms of external shading devices between maximum, minimum and average illumination levels (Lux) against each other and benchmark set out by CIBSE (2005) and CIBSE (1999).

Type of Shading	Minimum (Lux)	Maximum (Lux)	Uniformity (Average)	Average (Lux)-DL_1	Average Design Light Level Bench Mark in Accordance with CIBSE LG7:2005 (PC Screen & Paper text)	% Average Daylighting Reduction from Shading Against Base Case	Average Calculated Daylight Factor	Minimum Average Daylight Factor in accordance with CIBSE LG10 :1999
Basecase (No Shading)	35.58	4810.71	0.08	463.81	500	-	1.9	2
Horizontal	35.71	4180.94	0.08	427.32	500	7.87	1.8	2
Vertical	29.43	4650.41	0.07	402.40	500	13.24	1.4	2
Angled	21.59	3285.23	0.06	337.62	500	27.21	0.5	2
Multiple Angled (3No.)	12.09	822.98	0.1	121.75	500	73.75	1.7	2

Table 3- Daylighting Outputs for South Facing Windows (29th July)

The results shown in table 3 indicate there are higher levels of discomfort/disability glare from windows based on calculated maximum illumination levels. The best case solution is multi-angled shading as the maximum daylight calculated is reduced to 822.98 Lux. Although this value is significantly lower compared with other devices, the day light factor is higher than the vertical and angled types, almost equivalent to horizontal shading devices. In all cases artificial lighting is required to supplement the daylight contribution as the daylighting value is below 2 (CIBSE, 1999). When considering lighting energy consumption, table 4 shows calculated percentage reduction when comparing average artificial lighting and daylighting illumination (lux) values (DL_1/AL_1).

Type of Shading	Electrical Energy Reduction (%)
Basecase (No Shading)	89.88%
Horizontal	82.81%
Vertical	77.98%
Angled	65.43%
Multiple Angled (3No.)	23.59%

Table 4- Artificial Lighting Energy Reduction for Each type of External Shading (South Facing Windows) When Maximising Daylighting Contribution

Table 4 does not take into account uniformity and in reality luminaire rows closest to the window should be provided with dimming controls in order to regulate lamp lumen output. Luminaires to the rear of the room will still have to function at between 80-100% output to maintain illumination levels and uniformity.

Figure 9 provides comparisons between all device types for all different window orientations. The higher daylight factors are desired and horizontal shading type provides the highest daylight factor for all elevations. The bar chart shows multi-angled is second, vertical shading is third and angled type is worstcase.

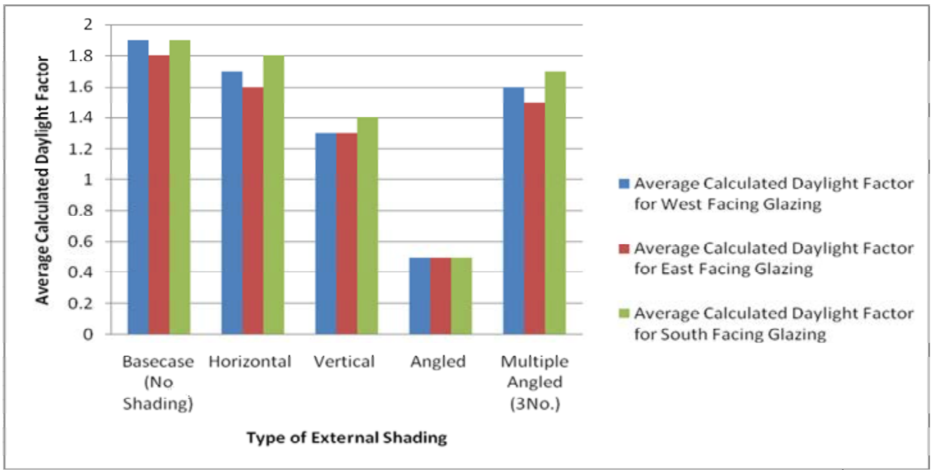

Figure 9- Average Daylight Factor for Various External Shading devices and Orientations (29th July)

5.3 Stage 1 Results Analysis

5.3.1 Solar Thermal Analysis

For solar thermal heat load reduction, the most effective solution observed is multiple angled type external shading for each orientation.

The daytime sensible cooling energy reduction for each external shading type compared against base case model is shown in table 5 below:

Orientation	Average Daily % Reduction Against Basecase- Horizontal Shading	Average Daily % Reduction Against Basecase- Vertical	Average Daily % Reduction Against Basecase- Angled Shading (45 Degree's)	Average Daily % Reduction Against Basecase-Multiple Angled Shading (3No. Slates at 45 Degree's)	Average Daily % Reduction Against Basecase- Internal Blind@50% Closed
East Facing Glazing	8.71	7.94	17.72	46.20	27.84
South Facing Glazing	15.15	10.42	21.40	41.16	27.42
West Facing Glazing	8.33	8.19	17.42	46.53	27.80

Table 5- Percentage (%) Sensible Cooling Load Reduction Based Upon Different Methods of Solar Shading

5.3.2 Effects on Daylighting

The values for average daylighting levels differ for each orientation and all instances the daylight factor is below 2; hence artificial lighting is required to maintain uniformity (CIBSE, 1999). From Table 3, the multiple angled shading (optimum solution) provides a reduction of 73.75% and provides average daylighting level of 121.75 Lux. As recommended by CIBSE (2005), the minimum lighting level required for the task (Computer screens and reading small text) is 500lux. The calculated daylight factor is only reduced by 10% when compared to the base case model. Also optimum solution only reduces artificial lighting energy consumption by 23.59% when compared to others which offer a greater lighting saving. The problem is there will be a considerable amount of glare (glare index >19) therefore the optimum solution also acts as external glare control measure. Further analysis of effects of this are not deemed necessary for stage 2 analysis.

6 Stage 2 Simulation- Analysis of Optimum Solution for All Elevation

6.1 Diurnal Cooling Energy Performance

For stage 2 dynamic thermal simulations, windows with optimum solar shading was added to East, South and West elevations. The model is represented below in Figure 10.

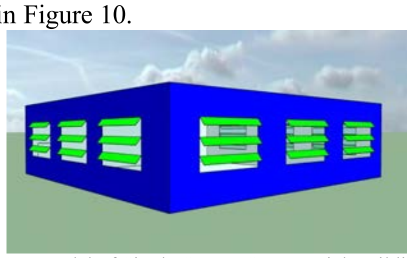

Figure 10- Model of Single Storey Commercial Building with Windows and Optimum Shading to East, South & West Elevations

Prior to the annual energy consumption being calculated, an analysis of the total daytime cooling load was completed and occupancy profile used. These are detailed in Figure 11 below.

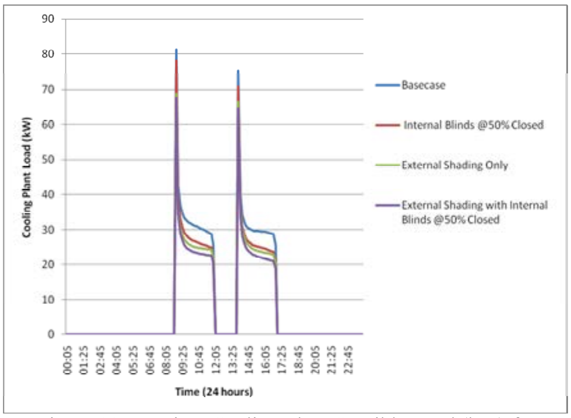

Figure 11 - Daytime Cooling Plant Sensible Load (kW) for Commercial Office (29th July)

The results above show sensible cooling load reduction for optimum external shading solution (multiple angled), internal blinds and combination of both. The average diurnal cooling load (Sensible) reduction is detailed below in Table 6, where the combined external shad and internal blind offer the highest reduction.

% Reduction Against Basecase-Internal Blind@50% Closed	% Reduction Against Basecase-External Shading Only	% Reduction Against Basecase-External Shading with Internal Blinds @50% Closed
13.41	17.80	22.93

Table 6 - Diurnal Sensible Cooling Load Reduction (29th July)

6.2 Annual Cooling Energy Performance

An annual energy performance (figure 12) was calculated and dynamically simulated for this building over an annual period.

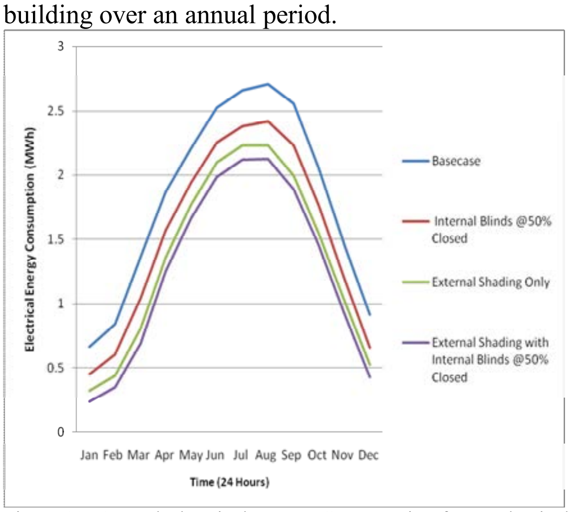

Figure 12 - Annual Electrical Energy Consumption for Mechanical Cooling

Cooling electrical energy reduction (%) are present in Tables 7 and 8 indicating energy savings against basecase. The table highlights monthly reductions, where in the hottest period (July), a 16.18% reduction can be obtained from the external shading and 20.32% reduction using a combination of optimum shading device and internal blinds. The higher percentage figures indicate a lower cooling levels leading to higher levels of saving, therefore only highlighted values (orange) should be used as a key performance indicators.

Month	Basecase	Internal Blinds @50% Closed	External Shading Only	External Shading with Internal Blinds @50% Closed
Jan	0.6645	0.45	0.3226	0.2399
Feb	0.8435	0.6028	0.438	0.35
Mar	1.3633	1.0444	0.8068	0.695
Apr	1.8666	1.5678	1.3618	1.2513
May	2.2099	1.9417	1.7716	1.6642
Jun	2.5267	2.2528	2.0952	1.9853
Jul	2.6596	2.3792	2.2294	2.1193
Aug	2.7084	2.419	2.2312	2.1234
Sep	2.56	2.2312	1.9973	1.8866
Oct	2.055	1.7645	1.5487	1.4541
Nov	1.4591	1.1993	1.0271	0.9306
Dec	0.9145	0.6603	0.5278	0.4311
Total	21.8312	18.5128	16.358	15.1306

Table 7 - Annual Electrical Cooling Energy Reduction (MWh)

Month	% Reduction Against Basecase-Internal Blind@50% Closed	% Reduction Against Basecase-External Shading Only	% Reduction Against Basecase-External Shading with Internal Blinds @50% Closed
Jan	32.28	51.45	63.90
Feb	28.54	48.07	58.51
Mar	23.39	40.82	49.02
Apr	16.01	27.04	32.96
May	12.14	19.83	24.69
Jun	10.84	17.08	21.43
Jul	10.54	16.18	20.32
Aug	10.69	17.62	21.60
Sep	12.84	21.98	26.30
Oct	14.14	24.64	29.24
Nov	17.81	29.61	36.22
Dec	27.80	42.29	52.86

Table 8 - Percentage (%) Annual Electrical Cooling Energy & Carbon Dioxide Reduction

6.3 Stage 2 Daylighting Analysis

A comprehensive daylighting simulation was carried out to determine the overall daylighting illuminace, overall day light factor and indoor illuminance. As shown in Table 9, effects on daylighting shows a reduction of 72.25%. This also indicates that the average illumination level is 351.46 lux contributes towards the required illumination level of 500 Lux at work plane level for lighting guidance 7 (CIBSE, 2005).

Type of Shading	Minimum (Lux)	Maximum (Lux)	Uniformity (Average)	Average (Lux)	Average Design Light Level Bench (LG7)	% Average Daylighting Reduction from Shading Against Base Case	Average Calculated Daylight Factor	Minimum Average Daylight Factor (LG10)
Basecase (No Shading)	253.34	5214.22	0.2	1266.36	500	-	5.3	2
Multiple Angled (3No.)	91.95	1250.84	0.26	351.46	500	72.25	1.5	2

Table 9– Optimum Solar Shading Effects on Daylighting

7 Conclusion

This work has been completed in order to determine the most effective form of external fixed solar shading using existing software tools. The theoretical models were created and dynamically simulated using IES VE software generated results and enabled further analysis to form the outcomes as detailed below:

- Multiple Angled shading is the most effective solution for commercial buildings in hot climates. The calculated diurnal cooling load reduction for East, South and West elevations are 46.20%, 41.16% and 46.53% respectively.
- Daytime cooling load (kW) reduction for stage 2 building is reduced by 17.80% using optimum fixed solar shading solution (Table 6).
- The most effective fixed external shading solution provides an annual cooling energy reduction of 25% and 30.69% using combination of external solar shade and internal blinds (Calculated from Table 7).
- Daylighting for effective solution is significantly reduced but still falls within acceptable levels in accordance with current standards.
- Provided artificial lighting is used, the optimum external shading day light factor is slightly reduced but still provides sufficient levels. This will also benefit by reducing disability/discomfort glare from windows (5,214.22 Lux max.) as shown in Table 9.

8 Further Works

Possible future research could be implemented for the following:

- ➢ Use hot humid climatic data to determine latent heat effects to shading device.
- ➢ Thermal comfort analysis.

9 Acknowledgements

The authors would like to thank their families for their support. This research required significant time and work, their patients is very much appreciated.

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