Proceedings of the 2014 Winter Simulation Conference
A. Tolk, S. Y. Diallo, I. O. Ryzhov, L. Yilmaz, S. Buckley, and J. A. Miller, eds.

ENERGY AND INDOOR COMFORT ANALYSIS OF VARIOUS WINDOW-SHADING ASSEMBLIES INA HOT AND HUMID CLIMATE

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ABSTRACT

Commercial buildings consume nearly 20% of all energy used in the United States, costing more than $200 billion each year. The building envelope plays a key role in determining how much energy is required for the operation of a building. Individual thermal and solar properties of glazing and shading systems only provide information based on static evaluations, but it is very important to assess the efficiency of these systems as a whole assembly under the site specific conditions. With an ever increasing cooling energy demand of buildings in hot and humid climates like in Florida, using a well-designed window-shading system is considered as an efficient strategy that minimizes the direct sunlight reaching indoors and thus reduces the overall energy loads. While reduction in energy loads is important, the indoor comfort of occupants should not be compromised. This research was conducted to analyze the indoor thermal and visual performance of various window-shading assemblies that were selected after their energy performance evaluation.

1 INTRODUCTION

Florida has become the nation's fourth largest commercial energy consuming state utilizing about a thousand trillion BTU's in commercial consumption and having a gross expenditure of over ten billion dollars per year in this sector (EIA 2010). Of the total energy that Florida produces per year, more than 90% comes from non–renewable sources like coal and gas contributing 4.8 million metric tons of energy related carbon-dioxide emissions from the commercial sector to the total emissions per year. In an effort to decrease the carbon footprint of this high commercial energy consumption, more stringent rules have been defined for envelope design in Florida Building Code Energy Conservation (FBC 2010). Much of the emphasis is given to the window to wall ratio, U-factor and solar heat gain coefficient (SHGC) of window glass and frame type while describing the energy efficient window strategies in section 502 (Building envelope requirements) of FBC 2010. Though there is a great potential for the advanced window systems such as switchable electrochromic or gasochromic windows in reducing the overall energy loads, still widespread use is unlikely to occur in the near future due to high initial cost and lack of technical expertise. Hence other related options such as automated shading systems could be deployed while still satisfying the thermal and daylighting requirements of the occupants.

Each face of a building requires a different shading treatment because the sun's angle of incidence is different on each face (Griffith et al. 2007; Huang et al. 2007; Raheem 2013). The past research has shown that the overall effectiveness of the sun-shading device depends on its performance for all sun positions (Karlsson et al. 2000, Huang et al. 2007). The proper use of shading devices may reduce the cooling loads by15-20% (depending on the amount and location of the windows) (Dubois 1997; Bourg 2008; Ali et al. 2012).

Studies have shown that indoor thermal conditions affect health, productivity and comfort of the occupants (EPA 1997, Fisk 2000, Gossauer et al. 2007, Gomez-Azpeitia et al. 2012). There are different variables that influence the thermal comfort of the occupants such as personal variables, environmental variables and physiological variables (ASHRAE 1985, Fanger 1986, ISO 1983). The personal and physiological variables are pretty much controlled/owned by the occupants. The effects of external environmental variables on the indoor comfort of the occupants can be controlled through a proper fenestration design. South façades are critical to design properly as during the day a large amount of energy from the sun is received through glazing and usually most of the sunlight gets concentrated in certain areas of the space if the facade is not properly designed (Littlefair 1995, Lawrence Berkeley National Laboratory 2014). This may result in glare on work surfaces causing discomfort for the occupants (Galasiu et al. 2006, Wienold 2006).

Individual thermal and optical properties of glazing and shading systems only provide information based on static evaluations but it is very important to assess the efficiency of these systems as a whole assembly under the site specific conditions. The main objective of this study was to investigate the impacts of these thermal and optical properties on the overall performance (energy consumption, and thermal and visual comfort) of south facing mid-rise office building in a hot and humid climate.

2 RESEARCH METHODOLOGY

The research was conducted in three phases: 1) modeling and simulation, 2) analysis and 3) comparison.

2.1 Modeling and Simulation

Software COMFEN 5 was used for modeling and simulation. This is an analysis tool based on EnergyPlus software and is used to evaluate the façade performance of commercial buildings considering different design scenarios. This software enables users to perform an energy analysis and simultaneously determine if the environmental control strategy will be sufficient for the occupants to be thermally comfortable.

The base model used in this research was a three storey office building with an area of 4000ft^2/floor located in Miami, Florida. The model was designed for the worst case scenario, i.e. south façade having a glazed curtain wall (glazing/façade ratio=0.67). The glazed wall was composed of an aluminium frame with 36 different window-shading assemblies comprising of four glazing and nine shading systems. The base model was simulated using nine different types of shading devices under three broad categories:

1. **Exterior shading devices**
   - Venetian blinds
   - Screen
   - Rolling shades
   - Overhangs
2. **Between glass shading devices**
   - Venetian blinds
   - Rolling shades
3. **Interior shading devices**
   - Venetian blinds
   - Screen
   - Rolling shades

2.2 Analysis

The building model was simulated multiple times for 36 different window-shading assemblies. The results were analyzed in terms of total annual energy consumption and heat gains through glazing. The most efficient window-shading assemblies were then selected to compare their overall performance.

2.3 Comparison

The results obtained through analysis were then compared to find an optimum window-shading assembly for the south façade with the least energy consumption and maximum indoor thermal and visual comfort. The comparison was made under two categories:

- Energy consumption
  - -Annual energy and peak demand impacts were investigated
- Indoor comfort analysis
  - -Thermal comfort
  - -Daylighting and glare

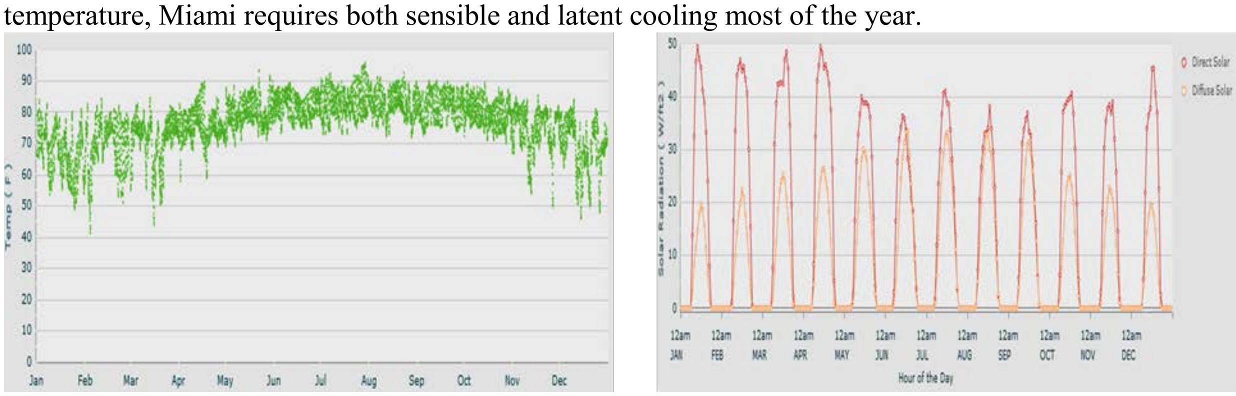
3 INPUT DATA FOR MODELING AND SIMULTION

Simulation software: COMFEN 5.0.5
Building Type: Office building
Geographical location: Miami FL; 25 49′ 26″ N 80 17′ 59″ W
IECC climate zone= 1
Heating and cooling degree days (U.S. census Bureau 2009) : HDD=149; CDD=4361
Building dimensions (LxWxH)= 80’ x 50’ x 30’

3.1 Weather Data

Weather data file used= TMY3
Required EnergyPlus file types= *.epw, *.stat, and *.ddy

The climate of Miami is essentially subtropical, characterized by a long and warm summer, with abundant rainfall, followed by a mild, dry winter. The annual temperature profile (Fig. 1) shows high temperatures during summer (above 90°F) with similar peaks of direct and diffuse solar radiations. Due to high outside temperature, Miami requires both sensible and latent cooling most of the year.



a) b)

Figure 1: Annual profile a) Dry bulb temperatures b) Direct and diffuse solar radiation. (Source: COMFEN 5.05)

3.2 Building Components and Space Properties

The ASHRAE standard 90.1 was used to determine envelope insulation requirements for the Miami climate (Table 1). The lighting and cooling load values were used as suggested in the ASHRAE guide for energy efficient small office buildings (ASHRAE 2004). The outdoor air flow rates used for ventilation were based on the area of the building (flow/area: cfm/ft^2) (ASHRAE 90.1). Average carbon emissions per unit of electricity (generated by utility and nonutility electric generators) and gas values were taken from data provided by the EIA (EIA 2002). The utility rates selected were an average price of electricity and used by end-user in the commercial sector (EIA, 2011b; EIA 2011a).

Table 1: Building components and space properties.

Input Data	Details	
Structural details	Steel stud wall with brick veneer Wall insulation= R-13 Glass/ façade ratio=0.67; Glass/floor area ratio=0.25 Glazing frame type= Aluminium profiles with thermal break	
Occupancy, lighting and equipment loads	Occupancy= 20 people Lighting= 0.9 W/ft^2 Equipment= 0.75 W/ft^2	
Cooling and heating temperature set points, °C	Cooling schedule For all hours = 26.7	Heating schedule Until 6:00=15.6 Until 22:00=21
HVAC system	Packaged single zone Flow rate based on flow/area= 0.3cfm/ft^2	
Utility rates	Electricity= $0.11/kWh; Gas= $1.03/therm	
CO_2 emissions	From electricity: 1.39 lbs/kWh; From gas= 0.12 lbs/kBtu	

Aluminum frames with thermal break were used and the thermal properties of the selected frame were representative of currently available commercial curtain wall systems (Table 2).

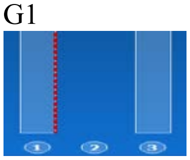
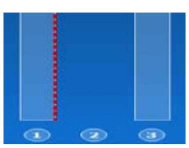
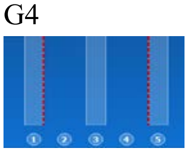
Table 2: Properties of shading and curtain wall frame.

No.	Shading		Curtain Wall Frame	
	Location	Type	U- value (Btu/h-ft^2-F)	Absorptivity
1	Exterior	Venetian blind 3” slat (slat angle 45°) Slat conductivity= 92.03 Btu/ h-ft-F Width-spacing-thickness= 3.03”-2.76”-0.04”	1.0003	0.9
2		Venetian blind 3” slat (slat angle 90°) Slat conductivity= 92.03 Btu/ h-ft-F Width-spacing-thickness= 3.03”-2.76”-0.04”		
3		Roller shade Solar transmission =0.15; Solar reflectance=0.3 Thermal Emiss. = 0.9; Conductivity= 0.17 Btu/h-ft-F Thickness= 0.03”; shade-to-glass distance= 3”		
4		Screen w/fine mesh (1mm)		

		Solar reflectance= 0.1; Conductivity= 0.17 Btu/h-ft-F		
5		Wall overhangs		
6	Between glass	Venetian blind 0.45” slat (slat angle 45°) Slat conductivity= 92.03 Btu/ h-ft-F Width-spacing-thickness= 0.45”-0.3”-0.04”		
7		Roller shade Solar transmission =0.15; Solar reflectance=0.3 Thermal Emiss. = 0.9; Conductivity= 0.17 Btu/h-ft-F Thickness= 0.03”; shade-to-glass distance= 1”		
8	Interior	Venetian blind 1” slat (slat angle 45°) Slat conductivity= 92.03 Btu/ h-ft-F Width-spacing-thickness= 1”-0.79”-0.04”		
9		Roller shade Solar transmission =0.15; Solar reflectance=0.3 Thermal Emiss. = 0.9; Conductivity= 0.17 Btu/h-ft-F Thickness= 0.03”; shade-to-glass distance= 1”		

The selected glazing systems had U-values ranging between 0.1 and 0.3 and SHGC below 0.5 with double and triple glass types (Table 3). These systems were comprised of multiple glass-gas layers and their thermal and optical properties like U-values, T_{vis}(visible transmission) and SHGC (Solar Heat Gain Coefficient) were calculated using WINDOW 7 software.

Table 3: Selected glazing systems for simulation.

ID	Glazing type	U-value (Btu/h-ft^2-F)	SHGC	T_{vis}	Thickness (in)
G1 	Double glass low solar low-E clear (Argon)	0.23	0.37	0.7	0.95
G2 	Double glass low T_{vis} low-E (Argon)	0.203	0.241	0.371	0.95
G3 	Triple w/suspended film; dual low-E	0.144	0.467	0.631	1.45
G4 	Triple, dual low-e; pyrolytic	0.145	0.3	0.541	1.67

4 ANALYSIS

The analysis was performed for four sets of window-shading assemblies while each set is comprised of one glazing system with all nine selected shadings (Fig. 2).

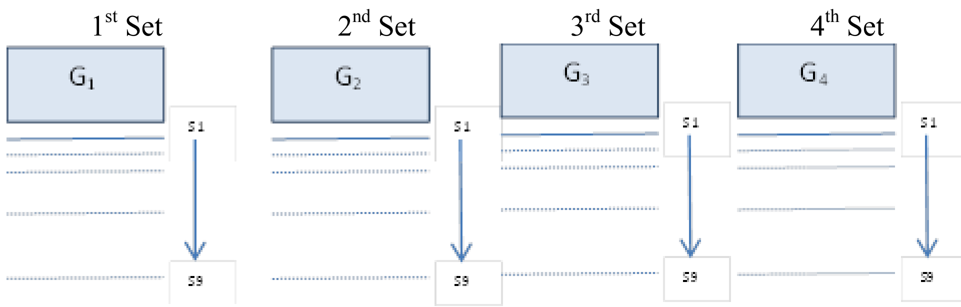
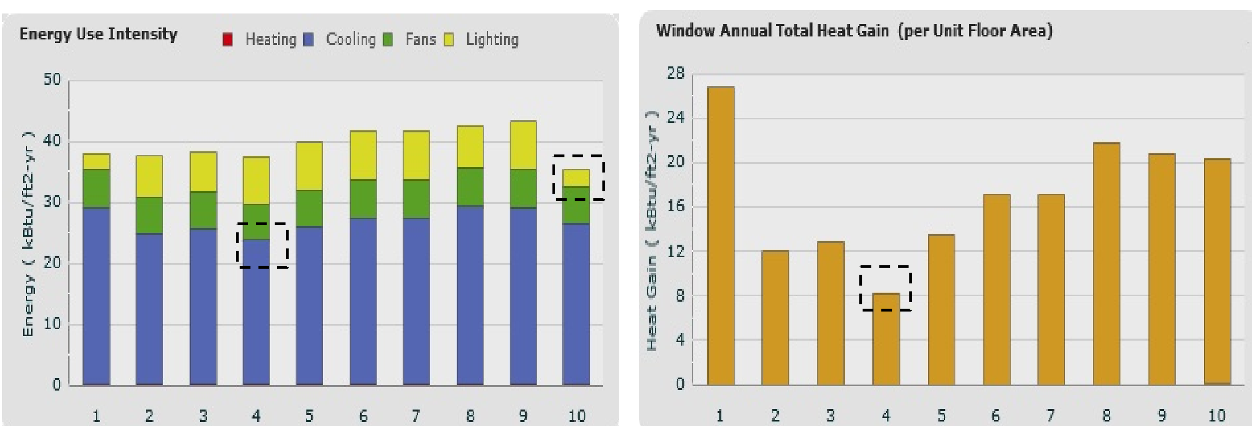


Figure 2: Four sets of window-shading assemblies.

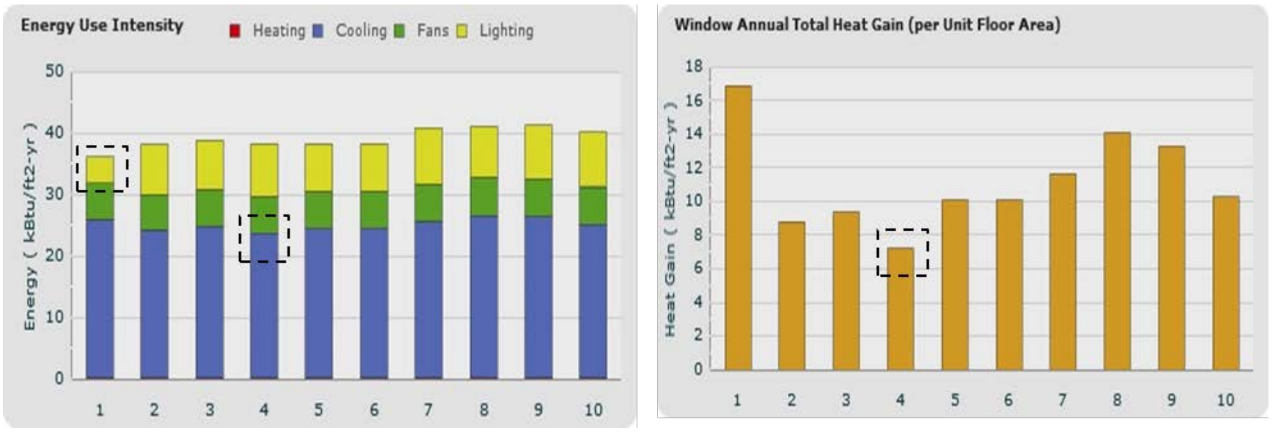
The energy analysis using four sets of window-shading assemblies provided. The energy consumption was measured for four energy usage categories: heating, cooling, fans and lighting. For the first set of window-shading assemblies, double glass (low solar low-E clear (Argon)) with nine different types of shading was simulated keeping all the other design and space parameters same in each simulation. It was observed that the least amount of total energy (for heating, cooling, fans and lighting) was consumed when overhangs(10) were used whereas exterior roller shades(4) were the most efficient ones in reducing cooling loads (Fig. 3(a)) due to the least heat gains through windows (Fig. 3 (b)).



a) b)

Figure 3: Analysis of the first set of window-shading assemblies a) Energy consumption b) Annual heat gains through glazing.Horizontal axis: 1-no sunshade; 2-External venetian blind 45°; 3-External venetian blind 90°; 4-External roller shade; 5-External screen; 6-Between glass venetian blind; 7-Between glass roller shade; 8-Internal venetian blind; 9-Internal roller shade; 10- Overhangs

For the second set double glass (low T_{vis} low-E clear (Argon)) with nine different types of shadings was simulated again keeping all the other design and space parameters the same in each simulation. The results in this case showed a decrease in the total energy consumption and window heat gains for each of the window-shading assemblies. It was further observed that the least amount of total energy (for heating, cooling and electricity) was consumed when no shading device was used. The cooling loads were not lowest in this case but lighting loads were reduced due to higher availability of the daylight, causing the lowest total energy consumption. Exterior roller shades were the most efficient in reducing cooling loads due to the least amount of heat gains through windows in this set as well (Fig 4).



a) b)

Figure 4: Analysis of second set of window-shading assemblies a) Energy consumption b) Annual heat gains through glazing.

Similarly third and fourth set of window-shading assemblies were analyzed and the optimum options were selected for comparison.

5 COMPARISON

Three best performing window-shading assemblies were selected from the four sets after analyzing their energy performance for the south facing glazed wall (Fig. 5). These assemblies were:

- Double glass low VT low-e (Argon) with no shading device (A1)
- Double glass low solar low-e (Argon) with overhangs (A2)
- Triple glass, dual low-e; pyrolytic (A3)

These selected assemblies were further compared for energy performance and indoor comfort on a monthly and annual basis.

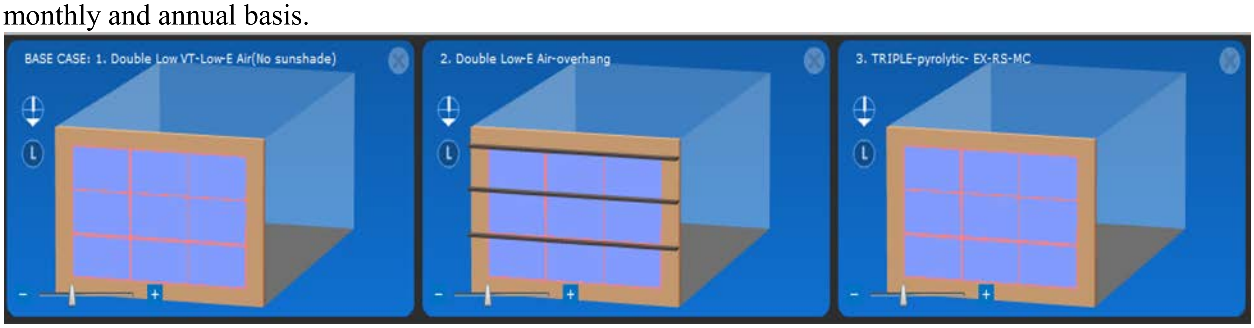
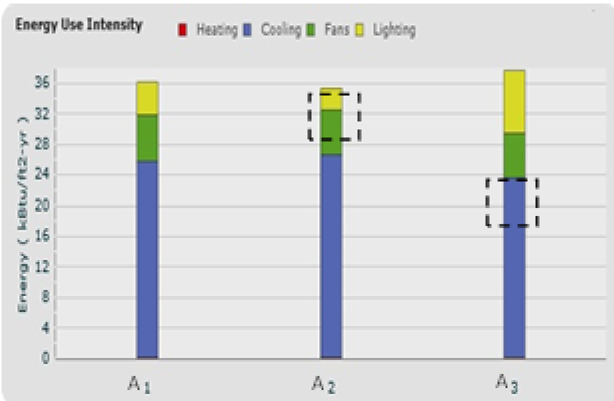


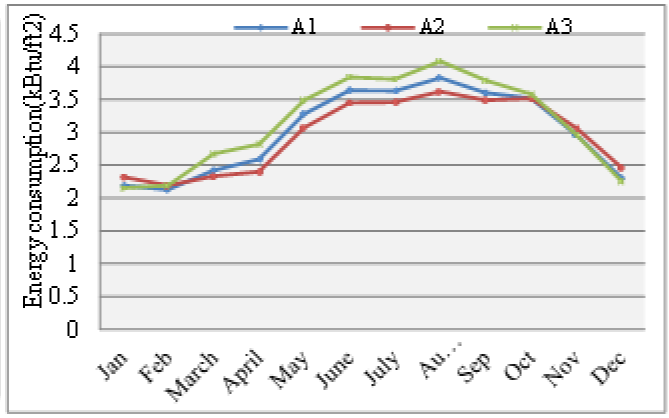
Figure 5: Window-shading assemblies selected for comparison.

5.1 Annual Energy Consumption

The total energy usage was calculated as the sum of the three energy use types (heating, cooling and electricity (fans and lighting). Based on the total energy use values, double glass low solar low-e with overhangs (A2) was the most efficient assembly in the current scenario. From the monthly energy consumption profile, it was observed that from March through September assembly A2 performed better than other two (A1, A3) but from Jan-Feb and Oct-Dec all the three assemblies were performing nearly in the same manner (Fig. 6) because the direction of conductive heat flow is from inside to outside of building during these months in Miami.



a)



b)

Figure 6: Energy consumption a)Annual profile b)Monthly profile.

5.1.1 Heat Gains Through Façade

The comparative analysis of annual heat gains through the façade showed very low heat gains (< 2W/ft^2) when A3 assembly was used which essentially means less cooling load throughout the year (Fig. 7).

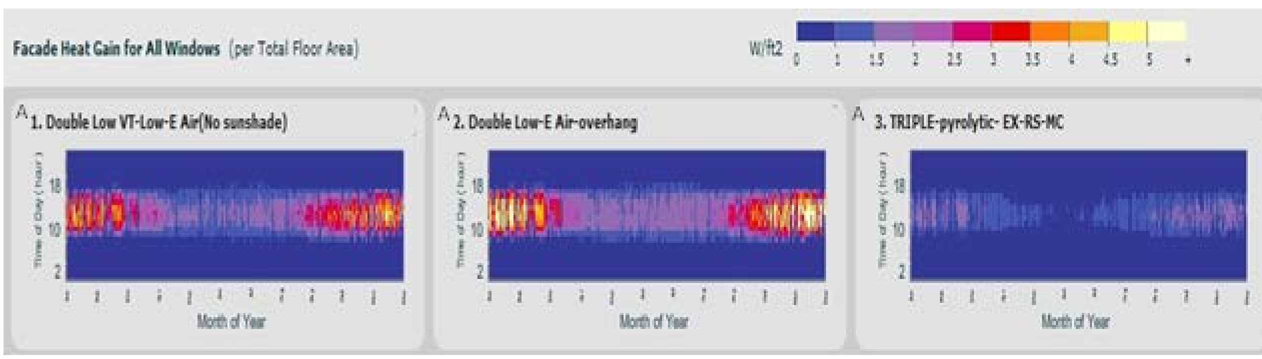


Figure 7: Annual heat gains through façade.

5.2 Indoor Comfort

5.2.1 Thermal Comfort

Three selected assemblies were analyzed in terms of thermal comfort and results were obtained as a percentage of people satisfied which is a direct output of the software used (Table 4). The A3 assembly was the most efficient one having the highest percentage of people satisfaction and least number of hours in a year when hourly temperature set points were not met (Fig. 8).

Table 4: Thermal comfort analysis.

	A1	A2	A3	A3 vs. A1	A3 vs. A2
Average thermal comfort (PPS)	86.37	85.09	88	>2%	>3.3%
Hourly temperature set points unmet (hours)	1173	1223	875	-289	-348

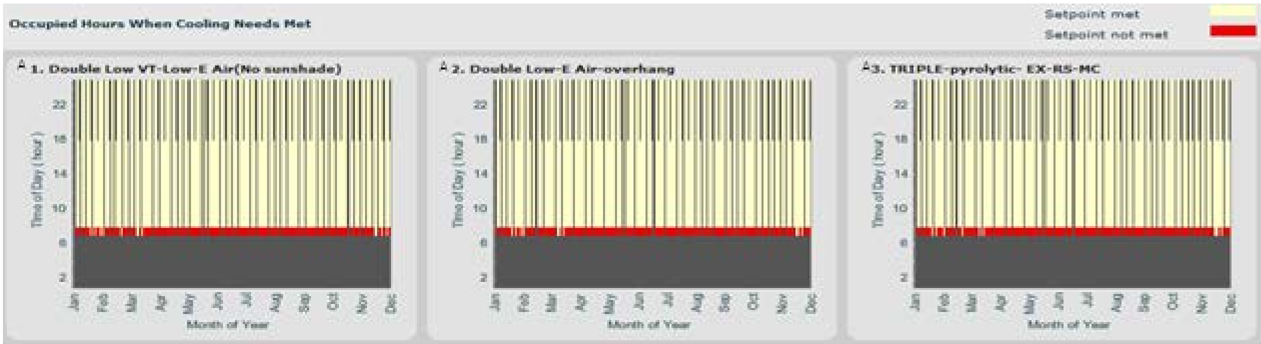


Figure 8: Occupied hours in the building when cooling needs are met.

5.2.2 Daylighting and Glare Analysis

A daylight analysis was performed for the selected assemblies and daylight illuminance maps were generated for a summer day (June 21st at 11:00AM). These maps were generated by the EnergyPlus engine working behind COMFEN software. These maps displayed work surface illuminances, calculated at 2'-6" (0.762 m) above the floor (default value), for the entire space in the form of a 10 x 10 grid (the grid is scaled to fit the space in the software). The maps showed high illuminance values for assemblies A1 and A2 near the façade area inside the office, whereas low, but uniform illuminance level was observed when using assembly A3 because the roller shades were on at that time of the day (Fig. 9).

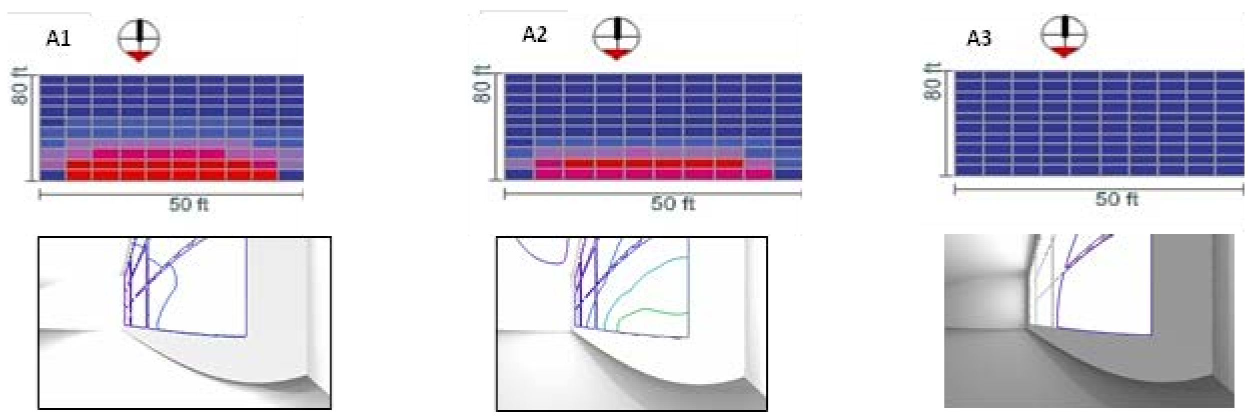
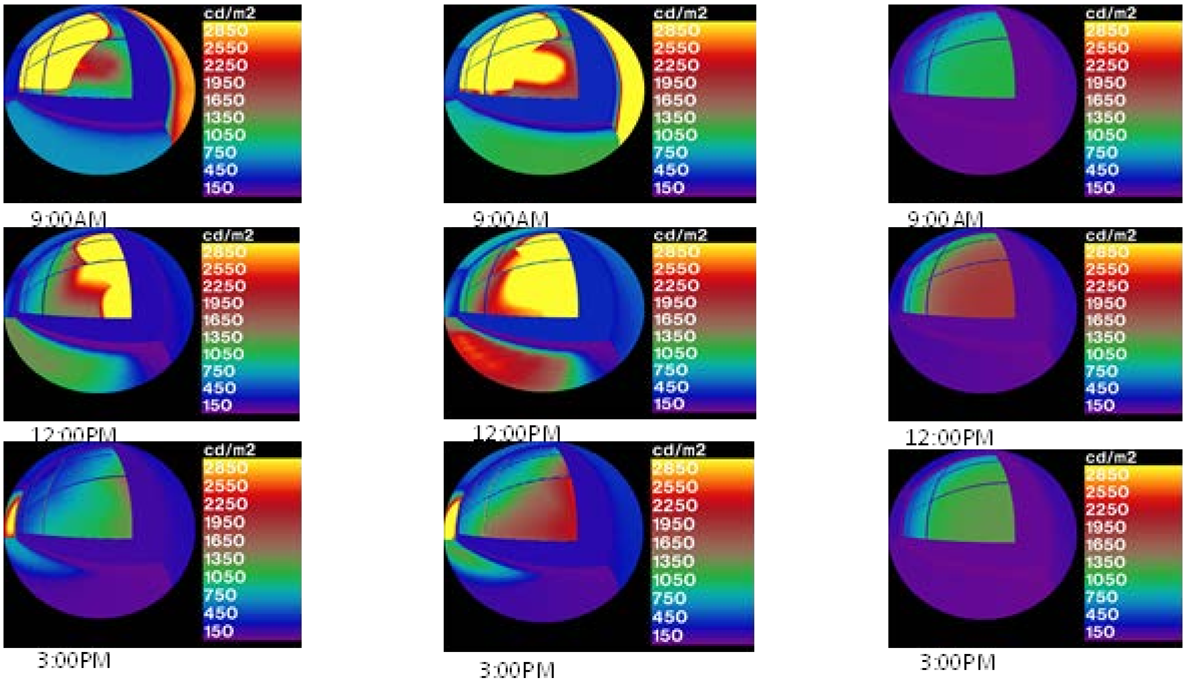


Figure 9: Daylight analysis- Top: Daylight illuminance maps; Bottom: Perspective view illuminance contour lines.

The selected window-shading assemblies were further compared to study the glare during the clear summer day from South side. The occupant's position (X=9.3,Y=15.6) and angle of view (X=6, Y=-9.6) were defined and point-in-time simulations were run for June 21st at 9:00AM, 12:00PM and 3:00PM (Fig. 10). It was observed that use of assemblies A1 and A2 caused really high values of glare during the morning and afternoon which is uncomfortable for the occupants whereas use of assembly A3 caused minimum glare values (≈55% less than A1 and 61% less than A2 at noon) throughout the day.



A1 A2 A3

Figure 10: Rendered images from Radiance showing luminance ranges for the selected assemblies (A1, A2, A3) during different times of a summer day (June 21st).

6 CONCLUSIONS

Although energy consumption is an important factor in evaluating building performance, the ultimate goal is to ensure the indoor comfort of the building occupants. This study looked at the effects of different window-shading assemblies for a south facing glazed wall in the hot and humid climate of Miami, Florida. It was observed from the analysis that shading devices behave differently (in terms of overall efficiency) with different glazing systems. For south facades exterior shading such as roller shades and overhangs are the most efficient options when combined with glazing systems having low U-value and SHGC (<0.3). The analysis also showed that although the least amount of energy was consumed annually when overhangs were used but they are not the best option in terms of providing indoor comfort for the occupants. More specifically the following conclusions were reached for the south façade window-shading assembly design:

- Glazing systems with a very low thermal and visual properties (visual transmittance (<0.3), U-value (<0.25) and SHGC (<0.25)) like assembly A1 used in this study can provide some degree of sun control without any shading device but can also increase glare and thus provide an uncomfortable indoor environment for the occupants. These systems can help in decreasing electrical loads but again the indoor comfort will be compromised.
- Glazing systems with relatively high visual transmittance (<0.8), low U-value (<0.25) and moderate SHGC (<0.4) (like assembly A2 used in this study) can work efficiently with fixed horizontal shading such as overhangs. Because of low initial cost, it may be preferred system however indoor comfort is compromised due to high glare during the morning and afternoon hours.
- The glazing systems with a moderate visual transmittance (<0.6), low U-value (<0.2) and low SHGC (<0.3)) (like assembly A3 used in this study) worked efficiently with external shades such as roller shades and venetian blinds to reduce cooling loads and permit filtered views. Because of

less conduction of direct sunlight (automated control), glare is reduced at times when horizontal solar angle is low.

In future, research will be conducted to compare the economic feasibility in terms of initial cost, energy cost and payback period of the proposed assemblies. Annual energy consumption data will be collected from a south facing office building in Florida and values will be compared with the results obtained after simulation of the models with the proposed window-shading assembly. Small scale experiments will also be carried out using sensor technology to measure the occupants comfort relative to the standard thermal and visual set points

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