Adaptive Shading Systems: Evaluating Lighting, Glare, and Thermal Control in Subtropical Environments

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Abstract

This study delves into the optimization and validation of a climatically computerized shading solution, aimed at balancing illumination levels, minimizing glare, and mitigating heat transfer through the building envelope. Prior research has scarcely addressed the employment of computerized geometries for optimal daylight control, glare reduction, and heat transfer mitigation. Our paper introduces an innovative shading design intended to boost spatial daylight autonomy and diminish daylight glare probability (DGP) through a blend of simulations, practical testing (utilizing a 6' x 6' x 7' / 1.8 m x 1.8 m x 2 m mock-up), and benchmarking against conventional louvers. The findings reveal significant reductions in average illuminance levels across three tested methods. Notably, the proposed shading system demonstrated a superior reduction percentage in DGP for the East and West façades when juxtaposed with traditional louvers. Additionally, surface temperature measurements disclosed a remarkable decrease of approximately 9% in temperature attributable to the shading system. This paper presents a cutting-edge shading system designed to enhance indoor environmental quality and visual comfort, marking a significant step forward in architectural design and environmental engineering.

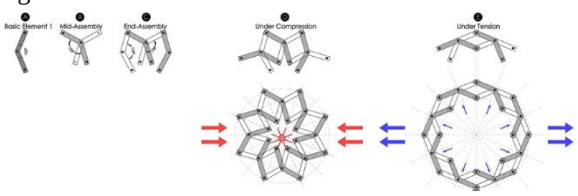
Introduction

The impact of building fenestrations on building energy performance and its indoor environmental quality (IEQ) is well documented. Acting as the "exchange agent" between indoor and outdoor environments, the building fenestration is responsible for majority of thermal interactions that take place between the built and the natural environment. Therefore, any improvements in its performance are critical to achieving higher energy performance and IEQ in buildings. In fact, due to their significant interactions with the ambient conditions, there has been tremendous interest in harnessing roofs, skylights, and fenestrations such as windows (Debije, 2010; Gutierrez & Lee, 2013; Gutierrez & Zohdi, 2014) in the push for higher energy performing buildings.

Building fenestrations have undeniable impacts on daylight admission, and consequently, indoor environmental conditions. Among all contributions that building fenestration can have on IEQ, the control of admitted daylight is particularly important given the extensive effects that daylighting can have on occupants' health and well-being. To capitalize on these effects, designers and engineers have developed "intelligent" building fenestration systems where the building components, such as shading systems, are designed in accordance with the outdoor environmental conditions. This research addresses the subject of climatically computerized shading systems and their contributions to illuminance levels, air and surface temperature in indoor spaces in the City of Gainesville, Florida. The main research questions are "what are the specifications of new structure, particularly in terms of geometry and pattern, which can produce sufficient illuminance while improving IEQ (minimizing glare)?" and "How computational simulation effectively address the challenges of shading systems and to what extent they are accurate in comparison with physical models?"

Geometry of structures and optimizations

This paper aims to develop a new shading structure where the geometric patterns and symbols are based on Islamic architecture. As shown in Figure 1, the top image shows a typical pattern. However, this pattern can cover a relatively small area, which can reduce its effectiveness to provide adequate shading. To address this problem, the geometry was advanced through changing the shape of basic element to a triangle, and hence, increasing the coverage area provided by the element. The bottom image of Figure 1 demonstrates new geometry pattern with additional surface areas, which can provide greater shading and subsequently daylight control.



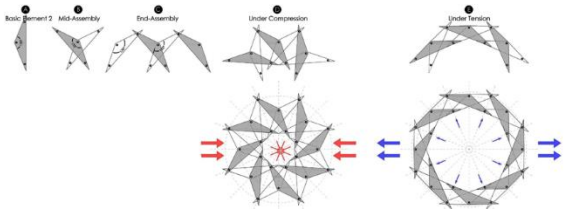


Figure 1 Typical pattern (top); Process of developing new geometry (bottom)

Current shading system are mostly either manually or mechanically controlled although they have significant limitations. The manual control system can remain irresponsive to changing outdoor conditions as it would require constant attention by building users to adjust the shading blinds. The mechanically controlled system can also underperform as easily due to potential malfunctioning of light sensors. Another option would be to utilize "smart materials" that automatically respond to varying outdoor conditions. Yi et al. (2018) showed a promising outcome for this method. However, these new materials are still in the developing stage and further research is needed before they can be implemented in building applications.

In this paper, a different approach was chosen to introduce a greater and more efficient responsiveness into the shading system. The method is finding an optimum configuration of shading geometry for a given location, which has been customized for that location and is able to reduce manual and/or mechanical interferences. For implementation, this paper uses Grasshopper, a plugin for a CAD tool called Rhinoceros (Robert McNeel & Associates, 2017) as CAD tool to control geometry. It should be noted that Grasshopper contains several plugins that allow users to utilize various functions without leaving the tool itself. This feature allows users to easily and seamlessly integrate different functions by eliminating the need to share information between different software tools, specifically, geometric information. The performance measure for daylight is Spatial Daylight Autonomy (sDA). To calculate the sDA of each measuring point, this paper uses a tool called DIVA (now being replaced by the Climate Studio) (Solemma, 2023). In addition to sDA, this study also uses Annual Sun Exposure (ASE) and Daylight Glare Probability (DGP). Wienold (2009) defines DGP ≤ 35% as the "class A", which is the best class where 95% of office time glare is weaker than "imperceptible". Therefore, in this study DGP of 35% was chosen as the criterion for glare. For optimization purposes, the paper uses another grasshopper tool called Galapagos. Galapagos is the built-in optimization application for Grasshopper and is used widely by designers. The Galapagos function will be further discussed in the following sections.

Methodology: Simulation/Experiment Setup

The test case study is a mock-up office, called "CoolBox™," due to its shading potentials, space placed in the University of Florida (UF)'s Energy Research and Education Park (Figure 2). The mock-up is 1.8 m wide × 1.8 m long with a height of 2 m and has fenestrations facing the East, South, and West orientations. Figure 2 shows the location of the CoolBox™, its baseline (without shading system), and proposed (coupled with shading system) configurations. It should be noted that the CoolBox™ is not equipped with any air-conditioning systems, nor it has any natural ventilation capabilities, rendering the model a completely "passive system."

Figure 2 Site map (top), CoolBox™'s exterior view (middle), and CoolBox™'s west façade with shading (bottom)

To conduct the simulation research, the CoolBox™ was computationally modeled within the Grasshopper environment, and daylight performance parameters including sDA, ASE, and DGP were measured for both the baseline and the proposed model (added new shading structure). The new shading system in the proposed model was later optimized to find the appropriate form of the shading structure, based on sDA (DA300 lux), ASE, and DGP given the specific location of the City of Gainesville, Florida (latitude: 29.6516° N, longitude: 82.3248° W).

The optimization process was carried out by Galapagos, which is one of the Grasshopper's commands, providing "evolutionary computing" for the geometry variables of the shading structure. The Galapagos is GA optimization used for single objective optimization, however, to optimize the shape and geometry of the new shading structure, the process focused on the extent with which simultaneously 1) ASE would be minimized, 2) sDA would be maximized, and 3) DGP would be minimized. To test a case that contains these three objectives for optimization through Galapagos, these objectives were combined into one single objective as following:

The governing equation for the objective function can be written as:

$$\min_{x \in X} f(x) = \sum_{i=1}^{n} (r_{ASE})_n + (r_{sDA})_n + (r_{DGP})_n = -1 \quad (1)$$

Where:

$$r_{ASE} = \frac{(r_{ASE})_n - 10}{100} = 0 \quad (2)$$

$$r_{sDA} = -\left(\frac{(r_{sDA})_n}{100}\right) = -1 \quad (3)$$

$$r_{DGP} = \frac{(r_{DGP})_n - 0.35}{0.35} = 0 \quad (4)$$

The objective is to maintain the ASE less than 10%; therefore, given equation 2, the minimum ASE must be 0. As for sDA, the greater the area percentage, the greater sDA. Therefore, according to equation 3, minimum sDA must be -1. As mentioned before, "class A" DGP requires a value less or equal to 35%. By using equation 5, the minimum DGP is determined as 0.

Therefore, the overall minimum value to be assigned to Galapagos, as indicated in equation 2, is:

$$(minimum\ ASE + minimum\ sDA + minimum\ DGP) = -1 \quad (5)$$

This research consists of a mixed-method simulation and field experimental measurement to validate the design optimization for new shading. A traditional louver system is also used to compare with the proposed shading system. The traditional louver was designed based on the altitude (77.69° and 36.55°) and azimuth angle (95.47° and 142.17°) of the research location, as shown in Figure 3(a). According to the calculation, the depths for south and east/west shading are 0.49 m and 0.18 m, respectively. It should be noted that the traditional louver system conducts simulation process exclusively in this study. The simulation process was fine-tuned with the modified geometry and dates, within the Rhinoceros environment utilizing Ladybug and Honeybee. The performance of the CoolBox™ coupled with new shading devices was tested for both lighting (illuminance levels) and thermal (indoor air and surface temperature) analyses. As for the illuminance research, initially, the computer simulation and field measurements (experimental research) of the CoolBox™ coupled with the shading system were conducted from June 20th to June 27th, at 8 AM, 12 PM, and 4 PM. Then, similar studies were carried out for the baseline model (without the shading system) from June 28th to July 2nd. Although the illuminance and thermal comparisons are made between different days (shading on: June 20nd – June 27th, and shading off: June 28th – July 2nd), according to weather data, these days had similar weather conditions (Weather Underground, 2022). To elaborate, the average solar radiation and ambient temperature difference between these two periods were 11.4 watts/m2, and less than 1°C, respectively, which are relatively small differences. Therefore, we can effectively compare the illuminance, air, and surface temperature on different days within the aforementioned time periods, which is attributed to expected differences between simulation and experimental research methods.

For both the computer model & field measurement, a 9-point grid [3 × 3, 0.45 m apart], and the illuminance values were measured at the aforementioned 9 points at the gird height. Thermal analysis (indoor air and surface temperature) was conducted simultaneously with lighting measurements for the same above-mentioned dates and times. To measure air temperature, 6 thermal sensors (HOBO sensors) (HOBO, 2022) were installed on the East, South, and West façade with three inside and three outside the CoolBox™. The sensors were installed at 1.8 m above the floor level on the outside of the box and corresponding location on the inside of the mock-up. As for surface temperature, a thermal camera was used to measure the surface temperature on three façades for both inside and outside (similar locations for air temperature sensors), meaning 6 surface temperatures were measured at each time spot (Sharston et al. 2023).

Glare measurements for the CoolBox, in conjunction with the shading system, were carried out between August 9th to 11th, 2023, at 8 AM, 12 PM, and 4 PM. Comparable measurements were executed for the baseline model (without the shading system) on August 12th, 13th, and 19th to ensure consistent sunny weather conditions. The glare image was captured using the LMK mobile, while the DGP was computed using LabSoft software (Techno Team Vision, 2023). The camera's height was set at 1.2 m, approximately at eye level in a seated position.

Results

Figure 3 (b) shows the best-case scenario with respect to the optimized new shading geometry. In other words, the geometry of the shading structure (Galapagos results) has produced the closest objective goal for the given number of geometry generations. As shown in this figure, the new shading structures demonstrate different geometry patterns for South versus East and West facades in response to different orientations and sky conditions. This variety can be attributed to the simulation requirement to limit the sun exposure at noon, where the sun altitude is high (75° at 12 PM) and limit the glare probability in the morning and afternoon, where the sun altitude is lower (13° at 8 AM).

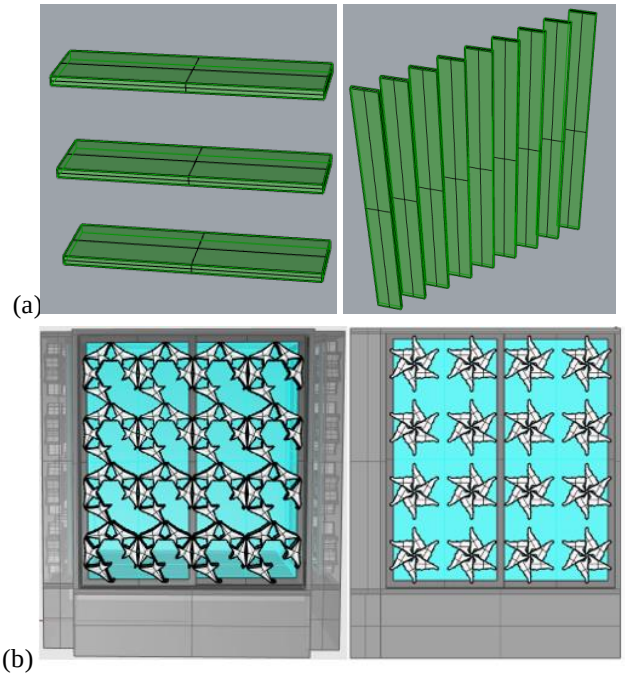


Figure 3: (a) Traditional louver system: South façade (left) versus East/West façade (right); (b) Optimized shading structure: South façade (left) versus East/West façade (right)

Horizontal Illuminance Analysis

The horizontal illuminance levels were measured, for both simulation and experiment, on the aforementioned 9-point grid, and then were averaged. It should be noted that the standard deviance of the 9 points' result is approximately 46 lux. Thus, we employ average value in the analysis part. The results are shown in Figure 4. According to the analysis result, it is evident that on most dates and times, for all three studies, the new shading has been able to effectively reduce the illuminance levels. As shown in Table 1, the shading system was shown to have reduced the average illuminance levels by more than 50% for all scenarios with 76.4% being the highest reduction taking place at noon for proposed shading's simulation, and 76.3% being the highest reduction at 4 PM according to the experimental results. The traditional louvers showed a similar reduction effect of illuminance. Table 1 also revealed that the indoor average illuminance level, while being reduced due to the effect of shading system, still largely remained within the range of 300-500 lux, which meets the Illuminating Engineering Society's (IES) standards for "office room" (Illuminating Engineering Society, 2020). The only lower illuminance level of 152.6 lux occurred on June 23rd at 4 PM for measurement. This day happened to have cloudy sky conditions, which is likely the cause of the low illuminance level. In summary, the new shading structure was shown to be able to reduce the illuminance level across the board by over 50% minimizing the probability of glare while still providing sufficient daylight-based illuminance for the space.

Table 1 Illuminance comparison between shading on and off period for proposed shading's simulation (top),

Figure 4 Illuminance comparison for proposed shading's simulation (top) and experiment (middle) and traditional louver's simulation (bottom) Note: the minimum recommended illuminance level for office room (source: Illuminating Engineering)

experiment (middle), and traditional louver's simulation (bottom) (unit: lux)

Shading / Time	Off (6/28-7/2)	On (6/20-6/27)	% of reduction
8 AM	13,284.87	5,502.24	58.6
12 PM	5,897.57	1,393.53	76.4
4 PM	11,060.69	4,500.09	59.3
8 AM	1,206.2	566.62	53
12 PM	823.2	372.04	54.8
4 PM	2,339	554.67	76.3
8 AM	13,284.87	5,816.79	56.2
12 PM	5,897.57	1,409.48	76.1
4 PM	11,060.69	4,757.44	57.0

Thermal Analysis

The effect of the proposed shading system on the thermal conditions was evaluated using two indicators, namely, air temperature and surface temperature. The results of air temperature-based thermal analysis are presented in Figure 5.

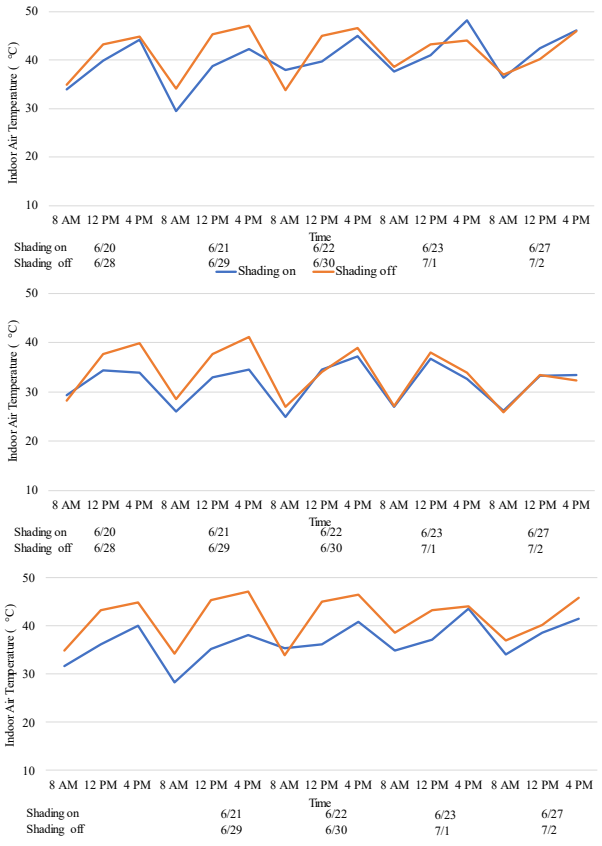


Figure 5 shows hourly indoor air temperature comparison among proposed shading's simulation (top) and experiment (middle) and traditional louver's simulation (bottom)

As shown, the indoor air temperature is lower when the shading system is in use compared to otherwise. However, a few "outliers" are observed in the simulation research (e.g. June 23rd at 4 PM). This can be attributed to the simulation observation made in Figure 4 (top) for the same date and time. From Figure 4, June 23rd is shown to have the highest illuminance levels compared to other simulation days, which is likely the result of direct sunlight. Therefore, we can potentially attribute the higher indoor air temperature on this date to the higher presence of direct sunlight despite having a shading system in use. With regards to the comparison between the simulation results and on-site measurements, the pattern of temperature increases and decreases with shading on and off is shown to be relatively consistent. Table 2 shows the hourly indoor air temperature for both shading on and off scenarios given different research methods, shading types, dates, and times. According to this table, the new shading system has been able to reduce the indoor temperature between 5% - 8% around noon and afternoon, while the traditional louvers have indicated a higher reduction percentage with 15.55% decrease around noon.

Table 2 Hourly air temperature analysis for proposed shading's simulation (top) and experiment (middle) and louver's simulation (bottom)

Shading / Time	Off (6/28-7/2)	On (6/20-6/27)	% of reduction
8 AM	35.73	35.08	1.82
12 PM	43.42	40.41	6.94
4 PM	45.68	45.17	1.12
8 AM	27.34	26.68	2.42
12 PM	36.19	34.38	5.00
4 PM	37.24	34.35	7.77
8 AM	35.73	32.85	8.06
12 PM	43.42	36.67	15.55
4 PM	45.68	40.84	10.61

The indoor surface temperature simulation and experiment are shown in Figure 6. Surface temperature measurements are the average temperature of the CoolBox™'s facades measured by the thermal camera. As shown in Figure 6, the indoor surface temperature is nearly consistently lower when the shading system is in use as compared to when the system is not operational. These results are shown to be supported by both simulation and experimental methods. The "outliers" to this conclusions appear to be June 23rd at 4 PM and June 27th at 4 PM. While the June 23rd scenarios can explained due to having a higher solar radiation, the June 27th observation needs further studies. Although, the traditional louver's simulation results showed a higher reduction capacity, as demonstrated in Table 3, the validation experiments for the traditional louver are still needed in the future studies.

Table 3 Hourly surface temperature analysis for proposed shading's simulation (top) and experiment (middle) and louver system's simulation (bottom) (. Negative values indicate temperature increase)*

Shading / Time	Off (6/28-7/2)	On (6/20-6/27)	% of reduction
8 AM	37.63	35.64	5.28
12 PM	46.36	41.77	9.92
4 PM	45.68	46.73	(2.30)*
8 AM	27.00	27.14	(0.51)
12 PM	37.56	35.45	5.63
4 PM	38.41	35.36	7.95
8 AM	37.63	33.59	12.03
12 PM	46.36	37.93	22.23
4 PM	45.68	42.08	8.57

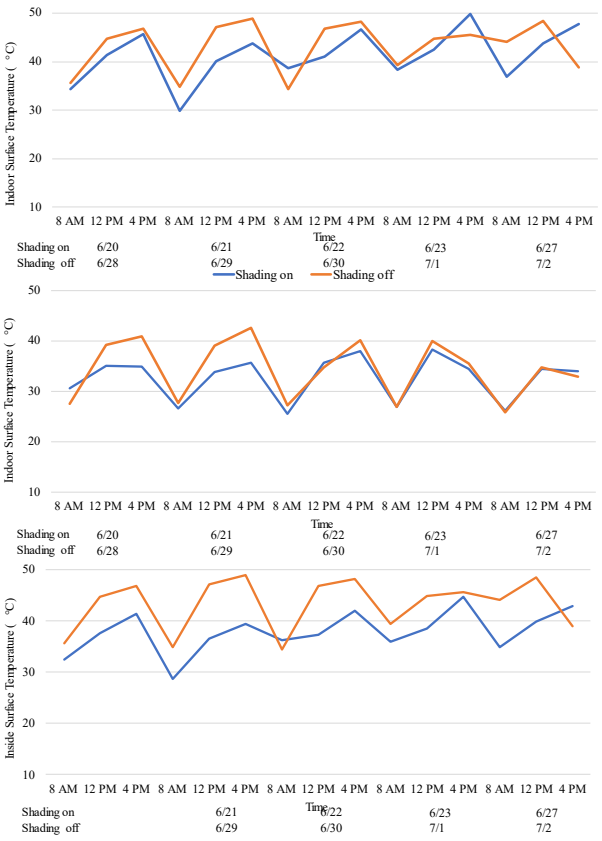


Figure 6 presents hourly indoor surface temperature comparison among proposed shading's simulation (top) and experiment (middle) and traditional louver's simulation (bottom)

Figure 7 shows the results of surface temperature field measurements for individual facades (as compared to the average surface measurements shown in Figure 6). To show the effects of new shading structure on the surface temperature for individual facades, two sunny days from each time period including June 20th (for shading on) and June 29th (for shading off) were selected (Figure 7).

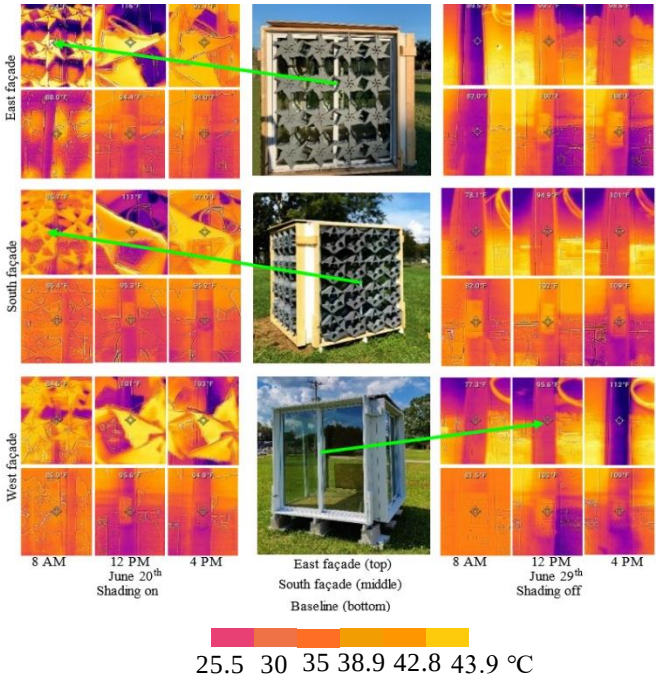


Figure 7 Surface temperature measured by thermal camera with exterior side (top rows) and interior side (bottom rows) for each façade

Glare Analysis

The images for calculating DGP were captured for 6 days with three shading on and three shading off days. The results of average DGPs were shown in Figure 8 and Table 4. For simulation, DGPs with shading system were well below the tolerance level regardless of time and orientation. The DGPs without shading system only exceeded the "tolerance level" of 35% at 8 AM on the east façade. The shading system reduces the DGP by 27.4%, 27.7% and 17.6% for east, south and west façade respectively, as demonstrated in Table 4. In terms of experiment results, DGPs with shading system on the east façade exceeded the "tolerance level" of 35% at 8 AM and 12 PM, which is considerably higher than the "class A" designation. Regardless of measurement time, the DGP for south façade with shading structure was well below the tolerance level. The DGPs for three façades without shading system all surpassed 35% with highest being 78.81% happened at east façade at 8 AM. The experiment results indicated that east façade has the largest DGP reduction effect as compared to simulation which happened on the south façade. It appears that the proposed shading structure is unable to fulfil the DGP requirements set by the optimization function for east and west façades, though, the shading system reduces the DGP by 38.5% and 27.8% for

east and west façade respectively, as demonstrated in Table 4.

Table 4 Average DGP of three façades comparisons analysis for proposed shading's simulation (top) and experiment (middle) and louver system's simulation (bottom)

Shading / Time	Off (8/12-13, 19)	On (8/9-8/11)	% of reduction
East façade	29.79	21.63	27.4%
South façade	25.92	18.73	27.7%
West façade	25.67	21.14	17.6%
East façade	61.02	37.52	38.5%
South façade	47.12	31.14	33.9%
West façade	46.53	33.61	27.8%
East façade	66.18	55.23	16.5%
South façade	46.52	30.73	33.9%
West façade	49.12	45.10	8.2%

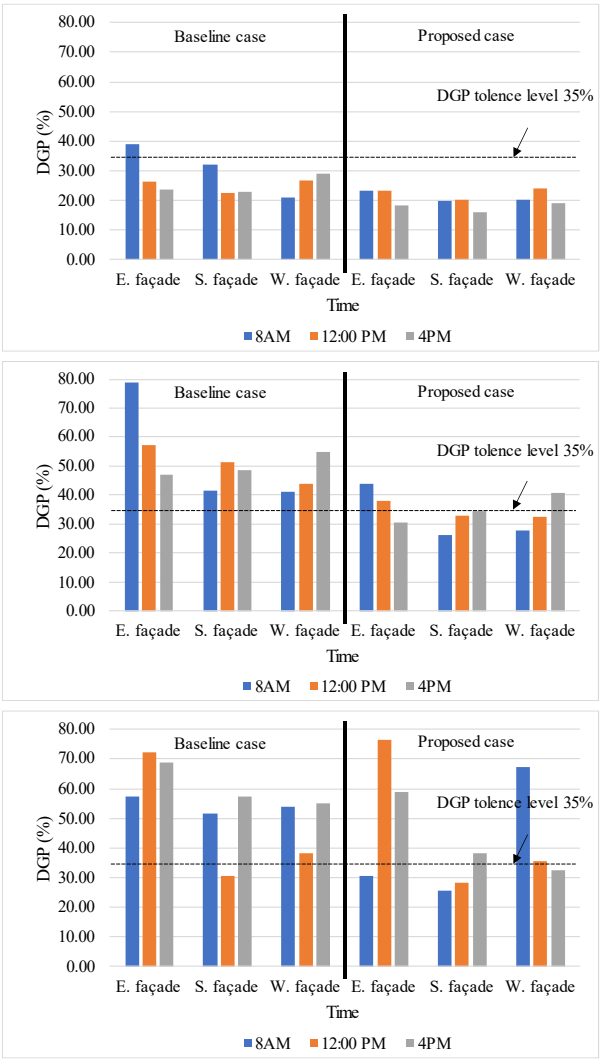


Figure 8 Average DGP values for both shading on and off period for proposed shading's simulation (top) and experiment (middle) and traditional louver's simulation (bottom) (E.: East, S.: South, W.: West)

Figure 8 also demonstrated the average DGP values of traditional louvers. The louver system reduces the DGP by 16.5%, 33.9% and 8.2% for east, south and west façade respectively (Table 4). Compared with proposed shading system, traditional louver system has less glare reduction for east and west façades.

Conclusion

This study has investigated the effects of shading structure with computerized and optimized geometries (simultaneously maximize sDA while minimizing ASE and DGP) on illuminance levels, indoor air, and surface temperature, and DGP in the City of Gainesville, Florida, USA. The proposed shading system's functions were validated through simulation, experiment, and traditional louvers' simulation. The simulation research involved using Grasshopper, DIVA, and Rhino (interface), while the field measurements were conducted for a mock-up, of the CoolBox™, installed at the UF's Energy Park.

The results suggest that the new shading structure can effectively lower excessive illuminance, solar radiation, and DGP, outperforming the baseline scenario while remaining environmentally responsive. The analysis of illuminance demonstrates a significant correlation between the reduction of illuminance (thereby reducing the likelihood of glare) and the effectiveness of the shading structure. This is in line with the illuminance criteria set by the Illuminating Engineering Society (IES). On average, the new shading structure, alongside the traditional louver system, managed to decrease illuminance levels by over 50%. This reduction significantly lowers the chance of glare, potentially enhancing the visual comfort of occupants while ensuring adequate daylight for the space. Notably, the new system achieved a marginally greater reduction in illuminance compared to the traditional louver system. Moreover, with the implementation of the new shading system, DGP was reduced by more than 27% for the east and south facades, and over 17% for the west facade. In comparison, the traditional louver system showed a lesser reduction capability, with decreases of 16.5%, 33.9%, and 8.2% for the east, south, and west facades, respectively. Furthermore, the thermal analysis also revealed a strong correlation between reductions in both indoor air and surface temperatures and the deployment of the new shading system. Specifically, the system was able to decrease indoor air temperatures by 5% to 8% around noon and in the afternoon during field experiments, potentially improving thermal comfort for occupants. However, simulation results for the traditional louvers indicated a decrease in indoor air temperature by 10% to 16% in the afternoon and around noon. The findings for the new shading system have been

corroborated by field experiments, underscoring the efficacy of the new shading structure in enhancing occupant comfort, albeit with slight variations in performance compared to traditional systems.

This new shading design marks the inaugural phase in the creation of an environmentally adaptive shading system. It's designed to interact with and respond to outdoor environmental fluctuations in real time, all while monitoring and satisfying the indoor requirements of occupants. Future studies on the CoolBox™ should aim to compare this innovative shading solution against its competitors. Such comparisons would help verify multiple functionalities of the new shading structures, including their resilience and energy efficiency.

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