MULTI-OBJECTIVE PARAMETRIC STUDIES OF EXTERIOR SHADING DURING EARLY DESIGN PHASES

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ABSTRACT

Utilizing building performance feedback as part of the preliminary design process can suggest environmentally responsive strategies and inform subsequent architectural development. This paper will outline a workflow that utilizes an integrated set of parametric design tools to simultaneously evaluate an exterior solar screen under multiple performance criteria, such as daylighting, visual comfort, energy, peak cooling, and shading effectiveness. The model captures the complex interactions between these performance aspects, the facade components, and occupant behavior as they affect and are affected by environmental factors. Without this integration, sub-optimal solutions may be selected based on misleading results.

The methodology for evaluating performance helps to define appropriate facade and shading properties, visualize performance, and set the stage for optimization in later design phases. The benefit of this multi-objective approach will be demonstrated within the context of previous project applications.

INTRODUCTION

Traditionally, energy simulation has been used as a confirmation of performance at the end of the design process. Incorporating simulation into the early phases of a project allows the design team to test the validity of various performance-based concepts to inform the design (Mahdavi and Lam, 1991). Sensitivity analysis of multiple options helps bring to light the appropriate climatic responses for the particular program and site, allowing the performance aspects to be one of the generators of the ultimate design.

Utilizing a design approach where sustainability strategies are part of the concept makes performance integral to the design. This allows the performative aspects to be the basis of design throughout subsequent stages (Mendler et al,, 2006).

Though there are many unknowns about the building in preliminary design phases, simulation can illustrate relative impact of various options without being too deterministic. These early studies can begin to identify the approximate range of various façade parameters to guide further development.

The value of early energy simulation is well recognized within the high performance design community (Schlueter and Thesseling, 2009). Early simulation is even beginning to be incorporated into leading green building rating systems. LEED v4, the latest version of the widely utilized green building rating tool, offers a credit for energy study models developed during the schematic design phase (USGBC, 2013).

Despite the theoretical advantages of an integrated simulation process in the early design phases, there are several practical challenges to implementation.

For example, there are usually separate models for the architectural design and for each of the different performance aspects such as energy or daylighting. Since the requirements for each analysis vary in terms of level of detail and geometry types, multiple models are typically used.

In early design stages, it is advantageous to study several variations to understand the best solutions. The need to rebuild or alter multiple models for each design iteration can be a deterrent to an exhaustive study of all possibilities, even during the early stages when performance analysis models are usually simplified “shoebox” studies. In addition, the lack of interconnection between the models can often lead to an absence of clarity of how the performance aspects affect each another (Bleil De Souza, 2009).

Optimizing one aspect may come at the expense of the performance of another. For example, increasing window to wall ratio may increase daylight illumination levels but adversely affect energy use or visual comfort if the additional sunlight is not adequately controlled. A study focusing solely on daylight performance may be blind to these unintended consequences.

To provide a more integrated analysis, parametric design tools can be used to combine multiple simulations into a single software environment. There are already existing plug-ins available for parametric software such as Grasshopper for Rhino (McNeel 2010) that integrate the design model with building performance simulation tools. Maximizing the potential of these tools to study the various performance aspects together in a comprehensive way can offer a better picture of the impact of various design decisions on performance.

Parametric tools allow users to keep their design fluid by defining relationships between elements while allowing the parameters of those relationships to be variable and easily altered. This affords them the ability to iterate and explore variation in the design, which can be a meaningful strategy within the context of optimizing performance.

The paper will outline a methodology used during schematic design phase of a project to study the effectiveness of an exterior louvered solar screen and discuss the useful conclusions yielded by an integrated process to inform further design development.

Project and Climate

The example project used in the following study is for 40-story mixed-use building in Ho Chi Minh City, Vietnam. The program of the building consists primarily of office space, a typology characterized by high internal loads from equipment and lighting.

Ho Chi Minh City has a tropical climate; it is consistently warm throughout the year and the relative humidity ranges from medium to high, averaging about 75%. Due to Ho Chi Minh City's low latitude, the sun will be at a high altitude for most of the day and will even take a northern path across the sky for part of the year. The amount of monthly solar radiation does vary slightly, but overall it is fairly consistent over the course of the year. The city experiences a high amount of solar radiation with a mixture of direct and diffuse components. See Figure 1 for an analysis of the solar radiation below.

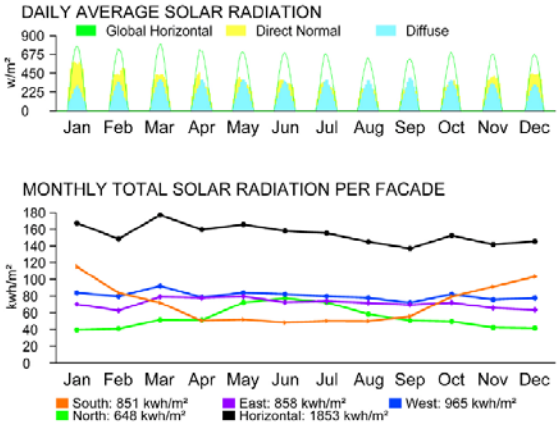

Figure 1 - Solar Radiation Graphs

In light of the high demand for cooling in Ho Chi Minh City, the climactically appropriate response is to reduce solar imposed loads as much as possible through exterior solar shading. Simultaneously, it would be advantageous to reduce internal loads by reducing the use of artificial lighting. The optimal solution would use the façade to balance both concerns: protecting from solar gains while maximizing daylight in conjunction with lighting controls.

Because of the orientation of the building's site, the tower is rotated 45 degrees from solar south, which complicates the solar control strategy since all of the primary facades have some exposure to low angle sun from the east and west.

The typical floor plate consists of two narrow open office bars linked by a central core. The shallow floor plate is a positive attribute for daylighting, but office areas that project from the core have three different exterior exposures, which increases the influence of the façade on energy usage since there is a high percentage of perimeter zone to floor area.

With all these considerations, it was determined that a vertical exterior screen should be investigated as a response to mitigate both the direct and diffuse solar radiation. The challenge for the design team was studying the performance of the screen, providing a methodology for optimization, and determining the best façade properties for the system to work together as an integrated whole. It was also important to be able to demonstrate the performance of the screen to the various stakeholders in a convincing and intelligible way.

Along with the screen, the properties of the glass were studied. A glazing unit with a low solar heat gain coefficient (SHGC) would help protect against solar gains, but would also carry with it a corresponding reduction in visual light transmittance (VLT) that may reduce the effectiveness of the daylighting strategy. There was also a concern that brightness at the perimeter may cause visual comfort issues and lead the occupants to keep the blinds down for most of the day, increasing the use of artificial lighting. The goal of the studies were therefore to find the approximate properties of the glass to work in conjunction with the screen to provide a reduction in brightness and solar heat gains while maintaining good daylight levels.

METHODOLOGY

Simulation

For the purposes of the study, a model of a typical office floor was created. A typical zone facing each of the four cardinal directions of the building was selected for a shoebox study model for analysis.

The façade elements such as the window to wall ratio and the physical properties of the exterior screen were constructed to be parametrically controlled to allow for the study of multiple design iterations. The positioning, density, and cross section of the screen elements were all variables, as was the thermal properties of the glass.

The parametric framework was set up to create the geometry for different types of performance analysis automatically. Any changes made to the design model would update the geometry required for the energy and daylight models with the corresponding changes.

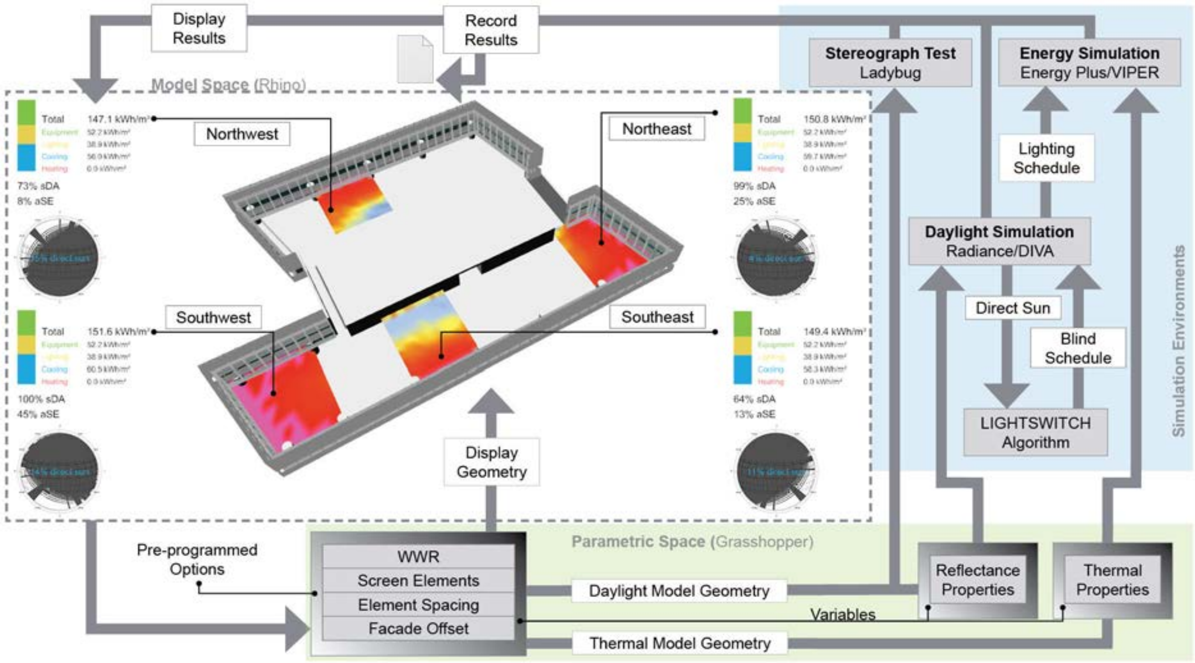

Figure 2 – Diagram of Integrated Model

The model was set up so that the different analysis simulations were linked with one another. The annual daylight analysis created a schedule for the interior lighting that was then used in the thermal simulation. Direct sun conditions on the interior would trigger interior blinds being pulled down by the occupants, which would consequently decrease the amount of daylight entering the space. The blinds would be controlled using the Lightswitch algorithm to predict occupant behavior (Reinhart, 2004). In this model, the occupants will pull down the blinds whenever they experience direct sun conditions on their work surface and leave the blinds down for the rest of the day. The algorithm assumes that the occupants will reopen the blinds every morning.

For the daylight and visual comfort studies, a Radiance-based simulation was performed using the DIVA plug-in for Grasshopper (Lagos et al., 2010). The energy studies were carried out by asingle zone model evaluated in Energy Plus through the Viper plug-in. To create stereograph diagrams for the shading options, the Ladybug plug-in was used (Roudsari, 2013).

There were several metrics used to measure the various performance aspects of the different scenarios.

Daylight autonomy (DA) was used as the daylight metric. The designs were evaluated based on the percentage of floor area that exceeded 300 lux for 50% or more of the occupied hours between 8 AM and 6 PM. Annual Sunlight Exposure (ASE) was used to measure the amount of direct solar radiation entering the space for visual comfort. Any part of the space that exceeded 1000 lux of direct illumination for more than 250 hours was considered to be problematic. The metric is described in the Illuminating Engineering Society standard IES LM-83-12 (Heschong L. et al. 2012) and is used as part of the daylighting credit in LEED v4, along with Spatial Daylight Autonomy (sDA), a similar metric to the floor area > $DA_{300lux/50\%}$ used here.

The energy use of each of the zones was normalized over their respective floor areas and reported in terms of energy use intensity (EUI) for cooling, lighting, and equipment (there was no heating required in this climate). The energy results were also parsed by the script to report on the peak cooling within each zone in terms of W/m^2.

Relative shading effectiveness was compared using stereograph diagrams. The diagrams where taken from a point a half meter in from the façade at desk level.

The simulations produced results files which were then returned back into the parametric environment and dashboarded automatically for each scenario. A conceptual diagram of the model's structure is shown in Figure 2 above.

Simulation Parameters

Five scenarios were created for study. The first was a baseline energy model based on ASHRAE 90.1 2007. As dictated by 90.1, this scenario had a 40% WWR, no exterior shading, and the baseline envelope thermal properties for Climate Zone 1. This scheme is mostly used in the conventional way to create a baseline to gauge energy performance but also to create a reference point for the daylight and visual comfort studies.

The second scenario was another reference case of a fully glazed building without any exterior shading. The glazing was a high performance clear glass with a fairly good SHGC. The third scenario used the same glazing properties but had an exterior screen that had 18% solid area. The fourth scenario was the same as the third but with a denser screen with 34% solid area. The fifth and final scenario had the 34% exterior screen but with a glass with a lower SHGC and VLT. All scenarios were simulated with and without daylight controlled dimming of the artificial lighting.

The simulation parameters can be found in the table below. It should be noted that the HVAC assumptions were kept the same for each scenario since the simulations were focused on studying the effect of the façade properties on solar imposed and internal loads irrespective of any mechanical efficiency improvements being proposed for the project.

Table 1
Simulation Parameters

Scenario	**1**	**2**	**3**	**4**	**5**
Scenario Name	**ASHRAE 90.1 BASELINE**	**NO SCREEN**	**18% SCREEN**	**34% SCREEN**	**34% SCREEN REDUCED VLT**
Envelope Properties					
Wall U-Value	0.436 W/m^2·K				
WWR	40%	80%			
Glass U-Value	6.81 W/m^2·K	1.0 W/m^2·K			
Glass SHGC	0.25	0.34			0.28
Glass VLT	0.71	0.61			0.52
Exterior Shading	No	No	18% Area	34% Area	
HVAC Properties					
Setpoint	24°C				
Cooling COP	3.0				
Infiltration	0.5 ACH				
Fresh Air	9.4 L/s/person				
Internal Loads Parameters					
People	0.1/m^2				
Equipment	11 W/m^2				
Lighting	11.74 W/m^2	10.65 W/m^2 (10% Improvement)			

Simulation time

The simulation time varies based on the type of simulation and the complexity of the exterior screen design.

The annual daylight simulation for each zone can vary from two hours to seven hours. An exterior screen with fine elements requires a high ambient resolution so that the rays bouncing between the screen elements are properly taken into account. This slows down the simulation considerably.

Although using the same Radiance-based calculations, each ASE simulation only took a few minutes. This is because no ambient bounces are required since the simulation is only studying the impact of direct sun.

Likewise, the energy simulation is very quick to run. Each scenario was run twice, once with and once without daylight-controlled lighting. Each run only took a matter of seconds for the single zone model.

Although the aggregated simulation time can be significant, the process itself can be semi-automated. The simulation can be set up to run each pre-programed iteration consecutively and record the results with distinct file names for later review.

Limitations

There are a few limitations to the methodology that should be noted.

The Energy Plus calculation is a single zone energy model where the loads are calculated and then divided by a simple coefficient of performance. This is sufficient to provide a relative comparison between the different façade options, but does not necessarily capture the complex interactions of the various HVAC system components the way a detailed energy model would. It also does not capture any thermal interactions between the zones.

The Energy Plus simulation also had difficulty with very complex screen geometry. Therefore, the parametric model was set up to automatically generate a vertical surface offset from the façade that was given an hourly solar transmittance value based on the screen geometry, solar position, and the percentage of direct and diffuse solar radiation as determined by the climate file. The parametric model would determine the open area of the screen based on the inputted geometry for each option. The diffuse radiation component was reduced by the percentage of solid screen area. The direct component was based on the sun position relative to the screen. The screen would be more transparent when the sun was lower in the sky, but would block more radiation when the sun had a higher elevation due to the thickness of the screen profiles. The direct and diffuse factors were combined and weighed by the percentage of each for each hour.

Another limitation to the process was that all of the complex lighting and interior blind operation controls of DIVA are not available within the Grasshopper components. This prevents the analysis from being conducted completely within the parametric environment, as would be the ideal scenario for this kind of study.

While the Grasshopper daylighting component can create a lighting schedule based on any of the analysis nodes falling below the illuminance threshold, it is difficult to choose specific nodes to be the daylight sensors or to divide a node group into separate lighting control zones for the perimeter or interior zones. The DIVA for Rhino blind control operation is likewise not available in the Grasshopper components at all and therefore required some manual intervention to take the operation of the blinds into account. To compensate, the daylight simulation was re-run in Rhino with separate lighting zones for the perimeter and interior of the floor plate. The simulation also allowed the effect of interior blind operation on the illuminance levels within the space to be incorporated. The lighting schedule generated was copied into the internal loads file to be used for the Energy Plus simulation in Grasshopper.

RESULTS

Daylight and Visual Comfort

The daylight results varied by orientation as indicated in Figure 3 below. In some cases, the exterior screens reduced the amount of area with a daylight autonomy over 300 lux for 50% or more of occupied hours for some zones. The effect was most detrimental on the northwest façade. However, the daylight area actually increased in the southeast zone with the denser screen and in the northeast zone with the denser screen and darker glass.

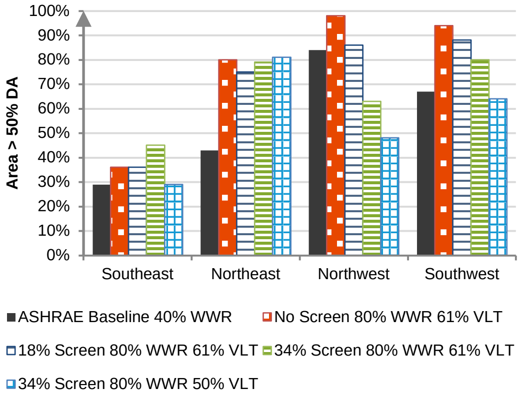

Figure 3 - Daylight Comparison, All Zones

This difference is due to the impact of the building occupants pulling down the interior blinds in response to direct sun conditions. The scenarios with the screen offered better direct sun protection for the interior and therefore the occupants pulled down the interior blinds less often. This preserved more daylight in the interior over the course of the year. Figure 4 shows a comparison of the unscreened and screened options with and without the effect of the blinds in the southeast zone.

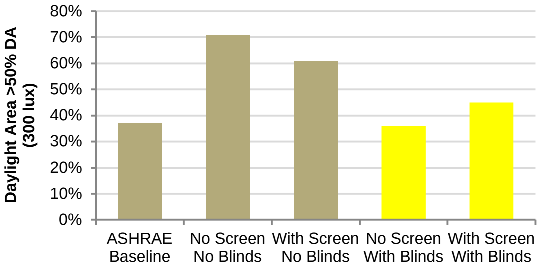

Figure 4 - Daylight Comparison, SE Zones

The daylight was reduced by the blinds in both unscreened and screened cases, but by a much lesser degree with the screened option. Without incorporating the effects of occupant behavior on the daylight, the results would indicate that the daylit area is higher without the screen, which may not be the case in reality.

The chart in Figure 5 indicates the hours of the blinds being open as predicted by the Lightswitch model. The unscreened option was consistently the worse performing of all the options. The northeast and southwest orientations had the fewest hours of opened blinds, indicating that they would experience the most hours of direct sun. The baseline case or the 34% screened options offered the most amount of hours with the blinds open. In the northwest zone, the blinds were open most of the time in all cases, indicating that there were few occupied hours with direct sun.

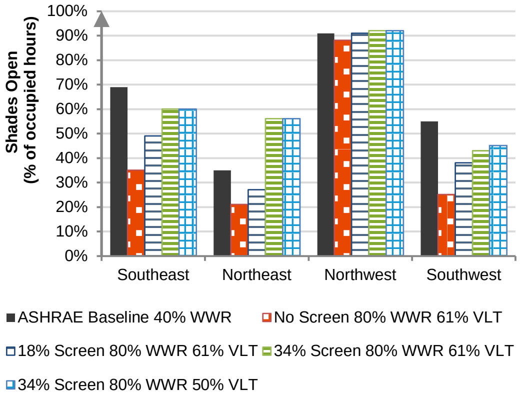

Figure 5 - Shade Schedule Comparison, All Zones

The exterior screen decreased the number of hours of direct sun penetration. The overlit area as measured by ASE metric was therefore decreased in the options that provided more solar protection. Figure 6 indicates the ASE in all four zones for each scenario. The ASE metric does not take into account interior blind operation.

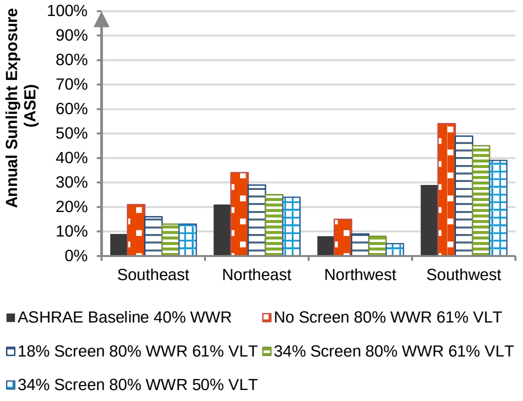

Figure 6 - ASE Comparison, All zones

The comparison of the ASE indicated that the glazed option without a screen consistently had the highest percentage floor area in direct sunlight. The options with the exterior screen performed better; in most cases the screen brought the percentage of overlit area back or close to the same level of the 40% WWR baseline case despite having much more glazed area.

The target ASE is 10% of the floor area or lower. It should be noted that the studies do not indicate what the overall building performance against the 10% target will be since there is more floor area that faces southeast and northwest than northeast and southwest. But the studies indicate the relative performance of the options and point out areas to focus on for improvement.

The southwest and northeast zones experienced the highest ASE results, even with the screen. This indicated to the design team that the narrower end walls could be treated differently than the bay with one exposure on the southeast and northwest facades. This could entail either using a denser screen or a darker glass on the southwest and northeast facades for more solar protection.

Energy and Peak Load

While the daylight studies were informative on their own, it was important to also see the impact of the daylight and screen on energy. Without taking into account daylight controlled dimming, the final option with the denser screen and lower VLT glass always consumed the least amount of energy. The unscreened option consumed the most energy, at a level higher than the baseline even with high performance glass and 10% reduction in lighting power density. The incorporation of exterior screen managed to reduce the energy use levels compared to the baseline despite the increase in glazed area.

When daylight controls were used, a more significant energy savings was achieved in both of the unscreened and screen options due to the shallow floor plate enabling good daylighting. The daylight controls also reduced the cooling energy use due to a reduction in interior loads.

Even though the screened options performed better than the unscreened option overall, the best performing screen and glass solution varied by orientation. On the southeast orientation, both of the 34% screen options consumed 137 kWh/m^2 annually, with the reduced cooling load provided by the darker glass being offset by an increase in lighting energy.

In the northeast, the denser screen and darker glass consumed the least amount of energy. The screen and lower VLT glass provided the best protection from the lower angle sun than all the other options studied.

Increasing the density of the screen and incorporating darker glass actually had a negative energy impact on the northwest zone when using the daylight controls. This indicates that there was not that much direct sun to protect from, and therefore the solar protection was only serving to reduce the indirect daylight in the space, reducing lighting energy savings. In this case, the best performing option was the less dense 18%

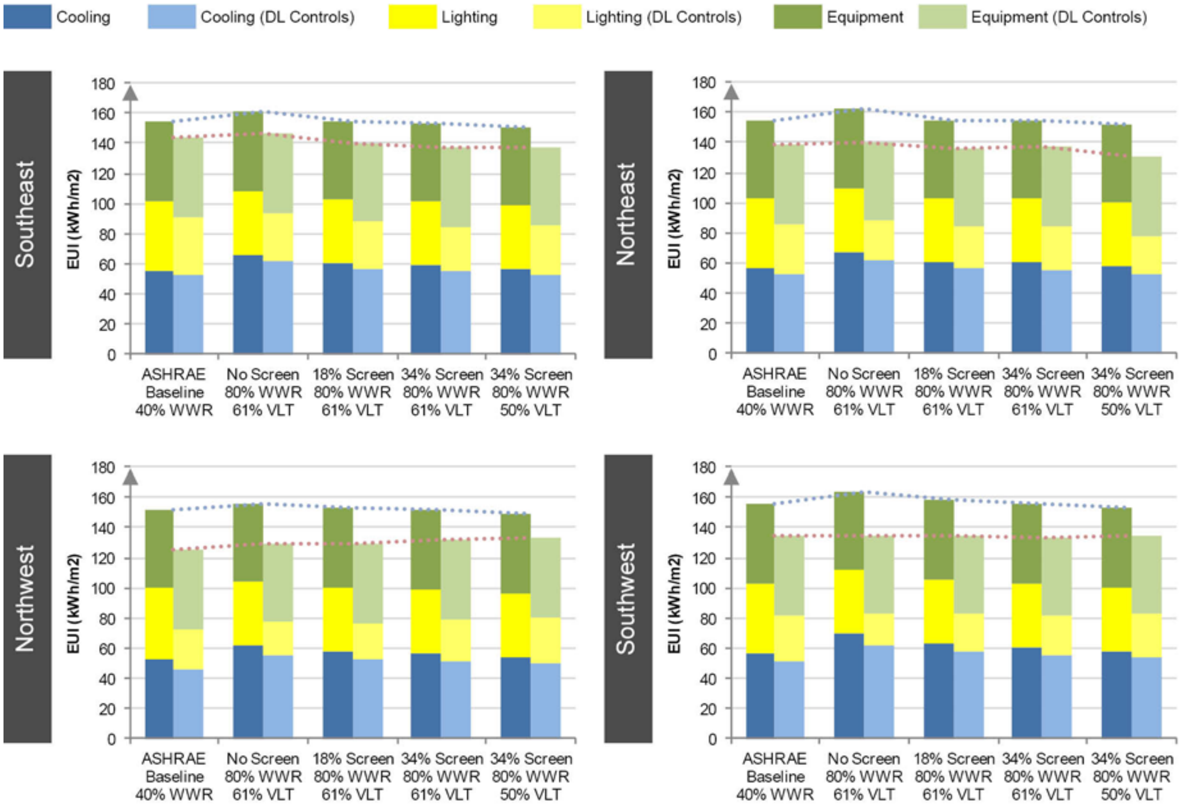

Figure 7 – Energy Use Comparison

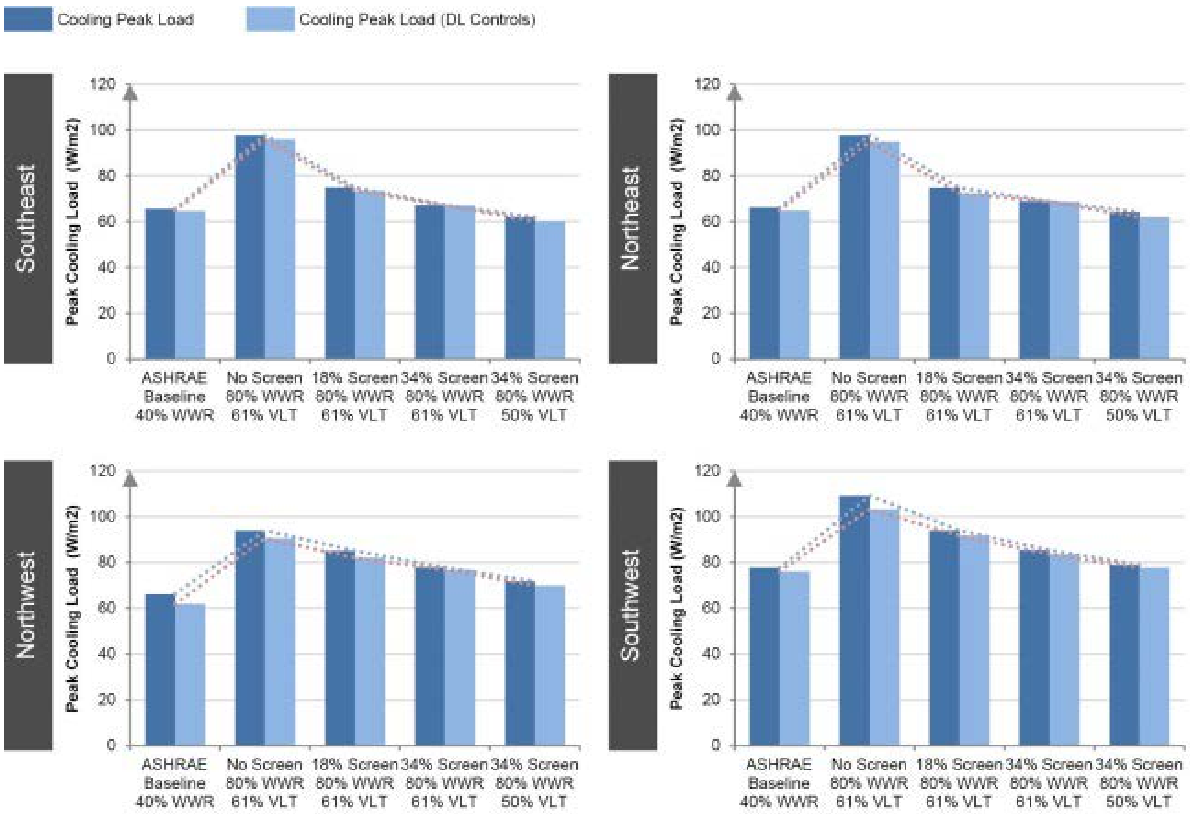

Figure 8 – Peak Cooling Energy Comparison

solid area screen.

Perhaps the greatest contribution of the screen besides improving visual comfort is the reduction in peak cooling loads. The screen options cut out a portion of the solar load, which shaves the peak cooling loads by as much as 33% versus the all glass version without the protection of the screen. This indicates that the screen can help reduce the cost of the mechanical plant and the size of the distribution systems, saving on initial project costs and space allocation. The option with the most solar protection, the 34% screen and the lower VLT glass, consistently had the lowest peak cooling load on all four orientations.

DISCUSSION

The integrated approach offers a potentially powerful methodology, especially when coupled with the ability to parametrically update all the performance models at once. The flexibility in the design model means that multiple scenarios can be studied in a shorter period.

The integrated model also allowed the study of the complex interactions between façade elements within the context of performance. Incorporating the influence of solar penetration on predicted occupant interior blind control with the daylight and energy models gave a better understanding of the influence all of these factors had on each other.

Without this element, it is possible that the unscreened options would have been given an overstated improvement in terms of daylight and energy performance since the lack of interior blinds would allow the electric lights to be turned off more often. This model better approximates reality where the direct sun and brightness would cause the blinds to be closed, negatively impacting daylight and hence increasing lighting and cooling energy consumption.

Another sub-optimal choice that could have been made without an integrated simulation approach would have been the selection of an even darker glass for solar protection. If the lighting and cooling energy savings from daylighting would not have been taken into account, reducing SHGC and VLT would have showed a corresponding improvement in energy use. However, the study indicates that 50% VLT starts reducing energy savings on some orientations and further reductions would have a deleterious effect because of the reduction in illuminance levels.

The results indicate where some of the trade-offs will be. On the northwest façade where direct sun occurs less frequently, more shading and a reduced VLT worsen daylight performance and hence increase energy use. Yet, like as with the other orientations, the peak cooling load is reduced with additional shading. Here the balance between energy usage versus peak load should be considered along with other metrics such as annual sunlight exposure for visual comfort.

Generating multiple sensitivity analysis provides an understanding of how the different components in the system affect performance. Even if changes occur to some of the parameters in the model, the studies provide enough understanding of the relationships between the factors influencing performance to better estimate if the effect will be positive or negative and what adjustments may be needed elsewhere to compensate.

The high ASE results on the southwest and northeast indicate that these facades could benefit from extra solar control. The healthy percentage of daylit area for these zones suggests that additional screening would not have a negative effect on daylighting, particularly on the northeast facade. Therefore, the methodology suggests a direction for further optimization of the screen as the design progresses.

While some of the current limitations in the tools used meant that some of the analysis needed to be performed outside of the parametric model, the abilities of available software is increasing. The Honeybee plug-in (Roudsari, 2013) has components that allow the interior blind analysis to be performed exclusively within the Grasshopper environment as well as multi-zone energy analysis. As functionality of the tools is expanded, there will be the potential for greater integration between the design and analysis.

CONCLUSION

An integrated analysis approach is useful to study multiple inter-related aspects of a building's performance. Taking into account the way in which those aspects interact with each other can provide a better picture as to the best design responses for a particular project and climate. The paper demonstrates that simplifying complex interactions can sometimes lead to sub-optimal decisions.

The studies were also useful in demonstrating concepts to all the stakeholders on the project and illustrating the connection between the design and performance. It showed that the screen provides the ability to filter light, blocking a percentage of the solar gains while admitting in indirect light. This provided both lighting and cooling energy savings while reducing peak load and the need for interior blinds. This meant the screen was viewed as an integral part of the building performance and unlikely to be removed from the project later on.

Employing such integrated methodologies in early design phases can allow performance to help guide the design development since it indicates the direction that the design should progress for better performance. If the performance is integrated into the design, the design process will ultimately be more successful at producing a building that is conceived as a response to its environment.

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