RESEARCH ON GUIDELINES FOR WINDOW DESIGN STRATEGIES IN HIGH PERFORMANCE OFFICE BUILDINGS

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ABSTRACT

This study presents an analysis of the daylighting and thermal performances of the window size and placement. In this study, a typical-sized office model with varing window sizes and placements (with the same window area) were selected to compare the abilities of different simulation tools that integrated thermal and daylighting simulation methods. The thermal and daylighting results from different simulation tools were analyzed and compared, and the best integrated thermal and daylighting simulation method was identified. Finally, a combined daylighting and thermal simulation guide is proposed for architects for the eveluation of window size and placement design strategies.

INTRODUCTION

In the past, there have been attempts to integrate thermal and daylighting simulation tools to achieve better results in combined daylighting and thermal performance. For example, the study by Koti and Addison (2007) demonstrated improved results by linking the DOE-2.1e (F. Winkelmann et al., 1993) thermal energy simulation and the DAYSIM (Reinhart and Walkenhorst, 2001) daylighting simulation versus what could be obtained by only using DOE-2.1e. The method they developed showed lower energy savings when the DAYSIM daylighting results were used instead of using the DOE-2.1e daylighting (Split-Flux) results for selected daylighting strategies. In another study, An and Mason (2010) integrated eQUEST (Hirsch, 2006) and DAYSIM. Their study showed that the combined simulation had higher energy savings than those simulated by DOE-2.2 using only the split-flux method. Since these combined simulation methods showed an improved performance, there is a significant motivation to use combined simulation methods to analyze the thermal performance of buildings incorporating daylighting strategies.

Unfortunately, in the previous studies the model and data exchange between the daylighting and thermal simulation programs were not fully automatic, which required passing model information and simulation results back-and-forth between tools. In general, the use of a combined Building Energy Simulation and DayLighting (BES/DL) analysis tools must first consider whether or not the tool is accurately modeling the daylighting and thermal design strategies.

The three most frequently used daylighting simulation tools are Split-Flux (Hopkinson et al., 1954), Radiosity (Tsangrassoulis and Santamouris, 1997), and Radiance (Ward, 1996). Today, Radiance is considered the most accurate daylighting sumualtion method compared to Split-Flux and Radiosity. However, Radiance is a very timing-consuming program, and it produces very different daylighting results with different rendering settings. Therefore, there needs to be a guideline for Architects to simulate the integrated daylighting and thermal performance accurately. This study developed a prototype for a combined daylighting + thermal simulation by comparing the existing combined simulation methods.

The sizing and placement of windows have a significant effect on the environmental behavior of a building, which includes the energy use for heating, cooling, and lighting. The building location, window material, orientation, and function of a building all affect the optimal design of the window size and placement. There are a number of research studies that have been conducted into the design of sidelight sizes, which include: Caldas and Norford (2002), Shan (2014), Mangkuto et al. (2016), Goia et al. (Goia, 2016; Goia, Haase, & Perino, 2013), Acosta et al. (Acosta, Campano, & Molina, 2016; Acosta, Munoz, Campano, & Navarro, 2015), and Pellegrino et al. (2017).

However, not all the previous studies considered the influence of window placement in the exterior wall (i.e., centered in the wall, top portion of the wall, or toward the vertical edges of the wall). In addition, some of the previous studies did not analysis how the daylighting affects the building thermal performance. Thus, there is a need to analyze daylite spaces using a sophisticated daylighting and thermal simulation tool to analyze the window placement and location in the both daylighting and thermal performances. Therefore, the purpose of this study is to propose guidelines for architects and engineers to accurately conduct the combined daylighting and thermal simulation to obtain a better window design.

METHODOLOGY

This study built a combined daylighting and thermal simulation by connecting Radiance and EnergyPlus

(Crawley et al., 2000) using the Grasshopper interface (Rutten, 2010). Then proposed a new prototype for the combined daylighting and thermal simulation process by comparing the combined simulation methods of DOE-2+ Split-Flux, EnergyPlus+Split-Flux, EnergyPlus+Radiosity, and EnergyPlus+Radiance. Figure 1 shows the steps for the proposed new prototype for the simulation process and tools.

to calculate the daylighting performance (F. C. Winkelmann & Selkowitz, 1985). In contrast, the daylighting calculations in EnergyPlus are performed using either a built-in split-flux daylighting module or using Radiosity (Ellis et al., 2004). The EnergyPlus+Radiance simulation needs the user to connect the two simulation program. Therefore, this study connected EnergyPlus and Radiance simulation

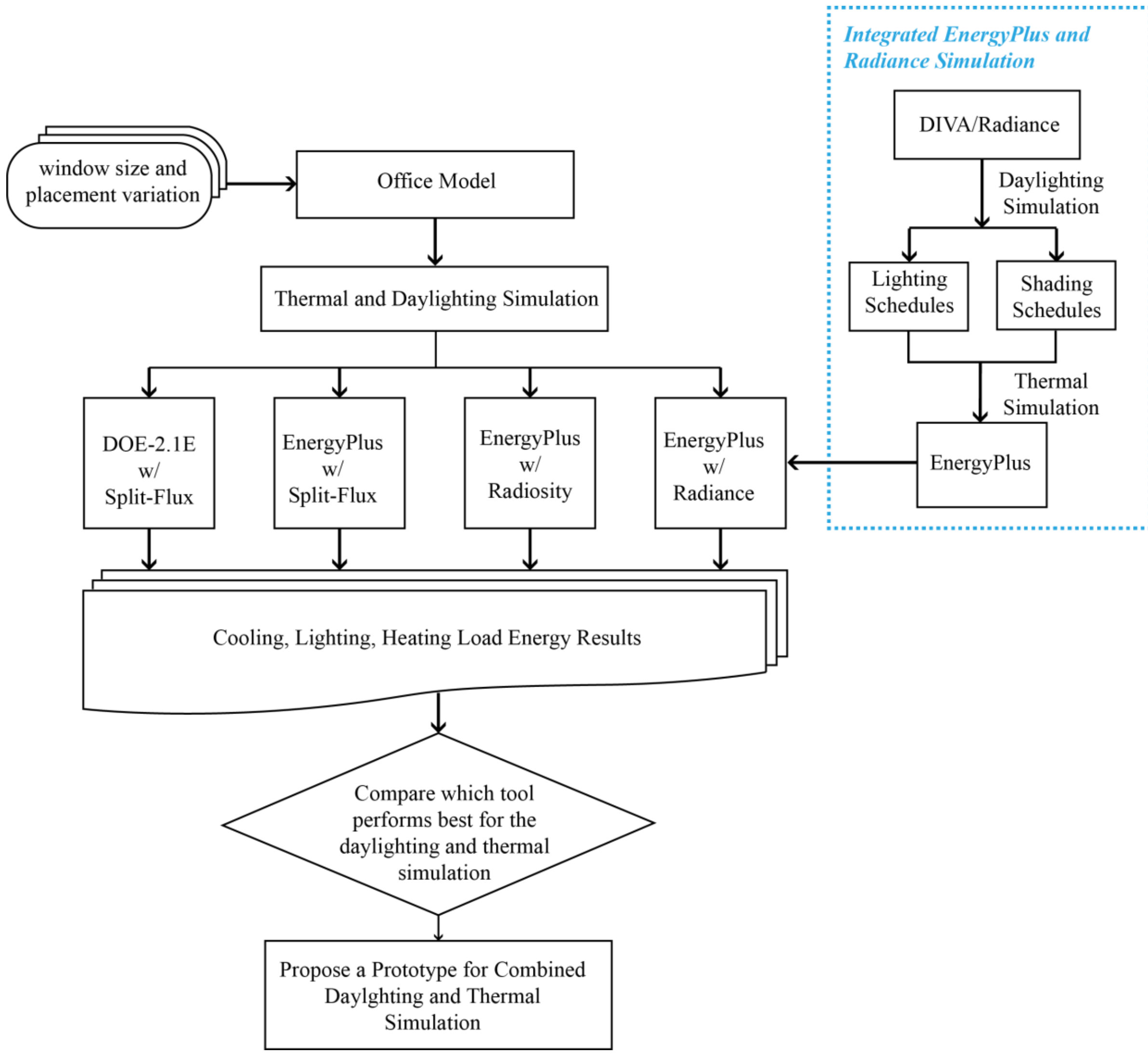

Figure 1 Proposed prototype for simulation process and tools

In the annlysisi, an office model with different window sizes and placements (but with the same window area) was tested to compare the simulation results from the various tools, which include: DOE-2.1e+Split-Flux, EnergyPlus+Split-Flux, EnergyPlus+Radiosity, and EnergyPlus+Radiance. DOE-2.1e and EnergyPlus are energy simulation tools that contain daylighting simulation programs. DOE-2 uses the split-flux method using the Grasshopper interface. In Grasshopper, Radiance and EnergyPlus can share the building model without model exchange. In this combined method, Radiance conducts the daylighting simulation to obtain more accurate results (i.e., lighting and shading schedules). Later, the results can be easily connected to EnergyPlus to obtain more precise lighting, heating, and cooling consumption.

Finally, this study proposed a prototype for a combined daylighting and thermal simulation method by comparing the results from different simulation tools.

SIMULATION

Figure 2 shows six types of window designs with the same window areas, where all window areas were 2.787 m^2 (30 ft^2). In window model 1, the window is located at the center of the wall. In window model 2, the window is located at the top of the wall. In window model 3, the window is located at the button part of the wall. Window model 4 is divided into two windows, these two windows are located at the two sides of the wall. Window model 5 also has two windows; one window is at the top part of the wall, another is located on the left side of the wall. Window model 6 has three windows; one window is at the top part of the wall; the other two windows are located on the two sides of the wall. All the annotation dimensions are shown in Figure 2. The remaining input parameters of the office model listed in Table 1. The lighting reference points are at the one third and two third depth of the room.

DOE-2.1e and EnergyPlus Settings

In the analysis, the DOE-2.1e and EnergyPlus input parameters were the same (Table 1). In the simulation settings, the equipment was turned-off, and the cooling and heating schedules were set as always on. The lighting schedule was turned-on from 8 am to 6 pm daily for all days of the week. The lighting power density was set as 11.95 W/m^2 (1.11 W/ft^2) based on ASHRAE Standard 90.1-2016 (ASHRAE, 2016). The simulation did not have occupants. In this study, the DOE-2.1e cooling and heating loads energy were obtained from the System Monthly Loads Summary (SS-A) reports of DOE-2.1e using the "SUM" system-type. In EnergyPlus, the cooling and heating loads were obtained from the "Zone Ideal Loads Zone Sensible Heating load" and "Zone Ideal Load Zone Sensible Cooling load" reports of EnergyPlus when the "ZoneHVAC: Ideal-Loads-Air-System" was used.

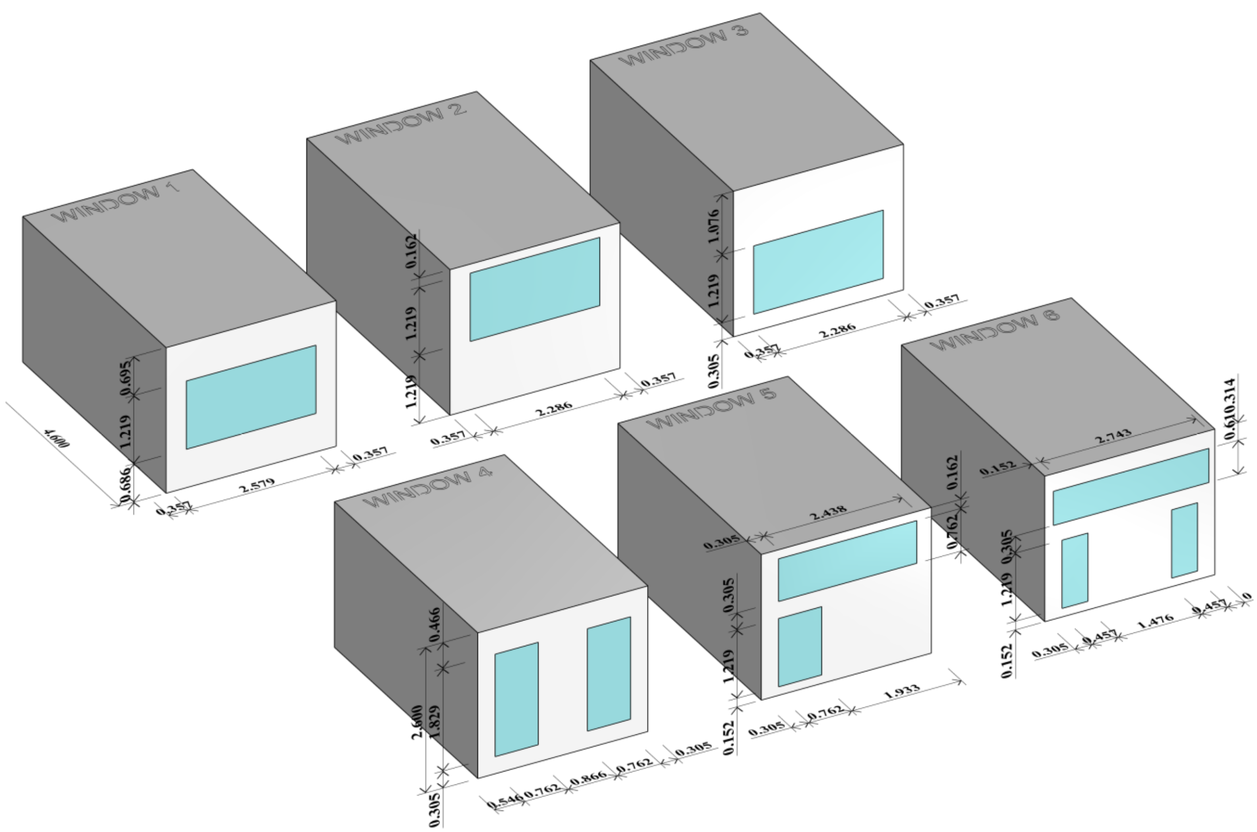

Figure 2 Six Window Model Dimensions

Table 1 The input parameters in the DOE-2.1e and EnergyPlus simulation

Parameters	Unit	DOE-2.1e	EnergyPlus
Room Length	m	3.0	3.0
Room Width	m	4.6	4.6
Room Height	m	2.6	2.6
Window area	m^2	2.787	2.787
Reference point height	m	0.762	0.762
Zone area	m^2	45.7	45.7
Volume	m^3	388.6	388.6
Roof U-factor	W/m^2-K	0.056	0.056
Floor U-factor	W/m^2-K	0.056	0.056
Exterior wall U-factor	W/m^2-K	0.288	0.284
Adiabatic wall U-factor	W/m^2-K	0.056	0.056
Floor visible reflectance		0.2	0.2
Glazing U-factor	W/m^2-K	1.34	1.34
SHGC		0.28	0.28
Visual Transmittance		0.41	0.41
Floor visible reflectance		0.2	0.2
Wall visible reflectance		0.7	0.7
Roof visible reflectance		0.7	0.7
Lighting power density	W/m2	11.95	11.95
Equipment	W/ m2	0	0
Illuminance dimming setpoint	lux	538	538
Occupants	People/ m^2	0	0
Cooling setpoint	ºC	25.6	25.6
Heating setpoint	ºC	22.2	22.2
Infiltration per zone	$m^3/s\text{-}m^2$	0	0
Outside air per zone	CFM	0	0
Assigned-CFM	CFM	Auto Adjust	Auto-size
System		SUM	Ideal-Loads-Air-System

EnergyPlus with Radiance

To combine the daylighting and thermal simulation, the Radiance (DIVA) (Reinhart et al., 2011) connected with the EnergyPlus (Ladybug & Honeybee) (Roudsari, 2016) in Rhino & Grasshopper interface. The lighting schedule from DIVA was connected to the EnergyPlus as a lighting input. In this way, EnergyPlus turns-off the daylighting simulation, and uses the lighting schedules from DIVA. In DIVA, the grid was above the floor at a 0.762 m (2.5 ft) height. The grid spacing is 0.3 m^2 (3.23 ft^2). Lighting sensors were set the same as the DOE-2 and EnergyPlus reference points. The lighting control system used was the photosensor controlled dimming. The photosensor controlled dimming assumes a dimming control has perfect knowledge of the illuminance from the daylight in the space, and the light is dimmed to meet the lighting target from a continuous dimming sensor with a user-defined setpoint. The illuminance setpoint in the simulation of the dimming control was 538 lux (50 fc). The Radiance rendering quality setting in this section was set as medium-quality, which results in relatively accurate result with acceptable software runtime.

SIMULATION RESUTLS

The simulation location of this study is in the hot climate zone (Phoenix, AZ). In this study, the windows were only placed in the South-orientated exterior wall. All other walls do not have a window. In the analysis, six window locations were tested with an equivalent window area (Figure 1). In order to test the importance of the floor visual reflectance settings in daylighting simulation, two different floor visual reflectance values were used, which were: 0.2 and 0.9. The simulation results from DOE-2.1e+Split-Flux, EnergyPlus+Split-Flux, EnergyPlus+Radiosity, and EnergyPlus+Radiance were compared. Table 2 lists the runtime of different simulation programs. EnergyPlus+Radiance took around 50 times longer to run compared with others.

Table 2 The simulation runtime with different simulation programs

Simulation Program	Runtime
DOE-2.1e + Split-Flux	0.05 mins
EnergyPlus + Split-Flux	0.10 mins
EnergyPlus + Radiosity	0.20 mins
EnergyPlus + Radiance	5.00 mins

Floor Visual Reflectance 0.2

For the lighting electricity use (Figure 3), without daylighting (grey color in Figure 3), all six window models have the same high annual lighting energy use. After integrating daylighting in the simulation, over 80% of lighting energy was saved. Therefore, there is a huge benefit to use daylighting in saving lighting energy use.

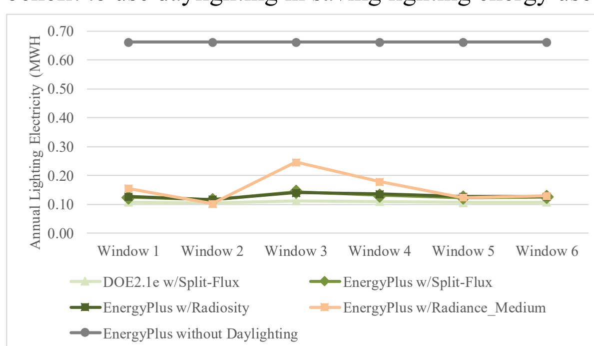

Figure 3 Annual Lighting Electricity Use with Floor Visual Reflectance 0.2 (South-Facing Window)

Comparing the simulation results with different simulation tools, the DOE-2.1e+Split-Flux simulation method and the EnergyPlus+Split-Flux/Radiosity methods obtained similar results for the six window models, which means there were no significant differences in daylighting performance when the window location changes. However, in the EnergyPlus+Radiance simulation results, every window model had a very different lighting electricity use. Window model 3 showed the highest lighting electricity use, while window 2 had the lowest lighting electricity use. These results show that the simulation results of EnergyPlus+Radiance were more sensitive to the window location changes. In window model 3 and window model 4, the lighting electricity usage predicted by EnergyPlus+Radiance was significantly higher than the usage predicted by DOE-2.1e+Split-Flux and EnergyPlus+Split-flux/Radiosity. These differences indicated that only the Radiance daylighting simulation differentiates windows 3 and 4 from the other window models. The common characteristic of windows 3 and 4 is that a larger portion of the window is nearer to the floor. When this lower window position is combined with the floor reflectance of 0.2, a significant variation in the lighting energy was shown for window models 3 and 4 (to a lesser extent) using the Radiance simulation.

Figure 4 shows the simulated annual cooling load for Phoenix, AZ. The results show that there was a very large cooling reduction when daylighting techniques were used. Therefore, daylighting helped in reducing cooling energy in a hot climate zone. It can be observed that the results from the EnergyPlus+Split-Flux and the EnergyPlus+Radiosity were almost the same. But the results from EnergyPlus (with Split-Flux/Radiosity) and DOE-2.1e have an approximate 9% difference with a higher cooling load predicted by EnergyPlus. This difference is most likely due to the thermal simulation difference between the DOE-2.1e and EnergyPlus. Without daylighting (grey color in Figure 4), all the other windows had similar cooling results, which means the window location changes will not affect the cooling energy. Accordingly, the DOE-2.1e+Split-Flux and EnergyPlus+Split-Flux/Radiosity obtained very simular lighting energy when window size and location changes were made, and the cooling usage from these simulation methods are almost the same. However, the lighting energy from EnergyPlus+Radiance was significantly different in all six models, thus, the cooling energy use of the six models had the same trends as the lighting energy.

In the same analysis, the heating load was smaller (Figure 5). This is because the analysis was in a hot climate location (i.e., Phoenix, AZ). In general, the results did not show a sensitivity to the window position. It is interesting to note that DOE-2.1e calculated around "0.0" total annual heating load, whereas all three EnergyPlus simulation methods calculated approximate 0.01 MWH/yr. The heating energy differences between with and without daylighting were very small as well.

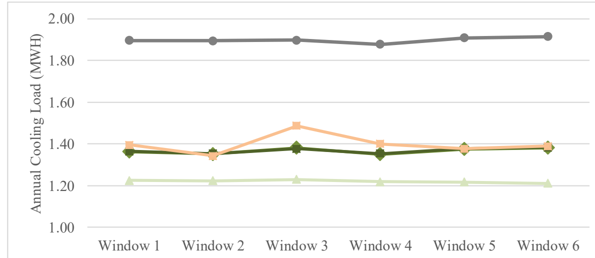

Figure 4 Annual Cooling Load with the Floor Visual Reflectance 0.2 (South-Facing Window, Phoenix, AZ)

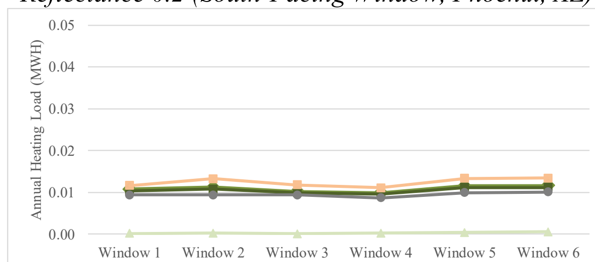

Figure 5 Annual Heating Load with Floor Visual Reflectance 0.2 (South-Facing Window, Phoenix, AZ)

Floor Visual Reflectance 0.9

When the simulations were repeated for a floor reflectance of 0.9, The results of the annual cooling load (Figure 7) and lighting energy usage (Figure 6) decreased dramatically in the EnergyPlus+Radiance simulation. In contrast, the annual cooling and lighting energy only dropped very little from the DOE-2.1e + Split-Flux and EnergyPlus+Split-Flux/Radiosity simulation. Therefore, the differences in the lighting electricity use decreased for all the combined simulation methods because of the increased floor visual reflectance. The lighting energy use calculated with the EnergyPlus+Radiance gave very similar results to the value of DOE-2.1e+Split-Flux and EnergyPlus+Split-Flux/Radiosity, which had been observed when the floor reflectance was changed from 0.2 to 0.9. For the window model 1, 2, 5, and 6, the Radiance simulation had almost the same lighting energy results with Split-Flux and Radiosity simulation. Only window model 3 gave higher lighting results from the Radiance simulation versus Split-Flux and Radiosity simulations (Figure 6). Therefore, when the interior surfaces were bright, the lighting results using either from Split-Flux or Radiosity or Radiance simulations were almost the same.

The cooling load decrease is because of the increased daylighting, which decreased the lighting energy use. The heating load (Figure 9) stayed about the same because it was too small to see the difference.

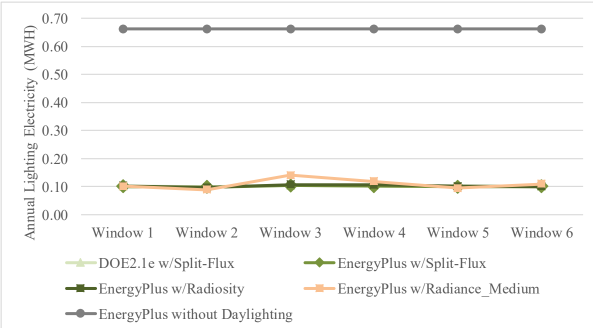

Figure 6 Annual Lighting Electricity Use with Floor Visual Reflectance 0.9 (South-Facing Window)

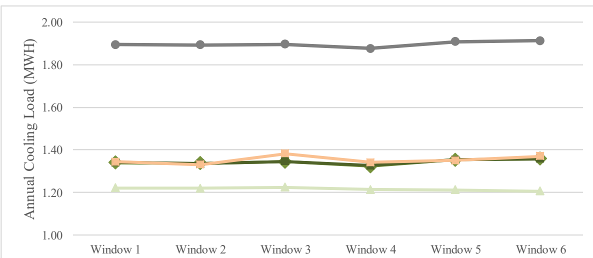

Figure 7 Annual Cooling Load with Floor Visual Reflectance 0.9 (South-Facing Window)

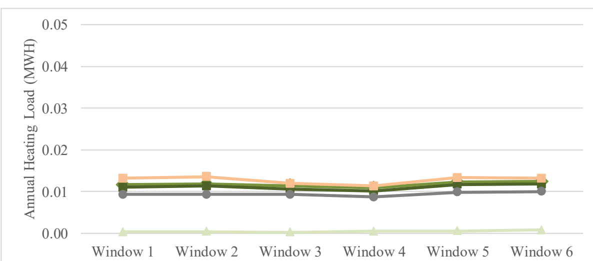

Figure 8 Annual Heating Load with Floor Visual Reflectance 0.9 (South-Facing Window)

ANALYSIS OF THE WINDOW LOCATION

Currently, the Daylighting Requirements in ASHRAE Standard 90.1 (ASHRAE, 2016) do not include guidelines and requirements about window size and placement. As a result, ASHRAE Standard 90.1 gives the same credit for a window in the center of the exterior wall, a window at the top of the wall, and a vertical window at the side of the wall. However, this study shows that EnergyPlus+Radiance had very different simulation results when the window location changes. Therefore, there is a good reason to make clear the differences. Table 3 shows the results of EnergyPlus+Radiance when the floor visual reflectence was 0.2 (dark floor surface). Window 1 is the base case, which is located at the center of the wall. When the window was changed to a location at the top of the wall (window 3), the cooling load was reduced 4.3%, and the lighting reduced was 37.5%. However, when window was located at the lower part of the wall, the cooling load increased around 6.4%, and the lighting electricity increased 56.3% compared to the window 1. Window 5 and 6 locations have similar cooling loads, but the lighting load decreased around 20%.

Therefore, the window located at the top or at the lowere (down) position of the exterior wall gives very different results than the window located at the center of the wall. Therefore, any architecture code/standard concerning window design should not give the same credits for all the window locations, a major conclusion from this study.

Table 3 Cooling and Lighting differences between window models (floor visual reflectance 0.2, Phoenix, AZ)

	Cooling		Lighting	
	Cooling Load	Differ.	Lighting Electricity	Differ.
Window1	1.4		0.16	
Window2	1.34	-4.3%	0.1	-37.5%
Window3	1.49	6.4%	0.25	56.3%
Window4	1.4	0.0%	0.18	12.5%
Window5	1.38	-1.4%	0.12	-25.0%
Window6	1.39	0.7%	0.13	-18.8%

CONCLUSION

In summary, this analysis tested six window models using four different combined daylighting and thermal simulation methods. The six window models were tested in a South orientation with different floor visual reflectance (i.e., 0.2, 0.9). In the analysis, the heating load energy was too small to be analyzed, while the cooling load energy decreased as the lighting energy decreased. Therefore, in this cooling dominated climate zone, reducing the lighting energy is important for reducing the total energy use.

For the South-facing windows, when the floor was a dark surface with a visual reflectance 0.2, the EnergyPlus+Radiance simulation resulted in a higher lighting energy use than the lighting results of EnergyPlus+Split-Flux/Radiosity and DOE-2.1e+Split-Flux simulation. In addition, the Radiance simulation is more sensitive to window location changes than the Split-Flux and Radiosity. In order to fully understand the window design stratageis, the EnergyPlus with Radiance simulation tool should be used when the floor visual reflectance is around 0.2 (dark surface). The analysis shows that compared to Radiance, the Split-Flux and Radiosity daylighting simulation methods over-calculate the illuminance in the interior space when the window was in a low position. That is because in Split-Flux is an empirical formula for calculating the Internal Reflected Component (IRC), which does not consider window position relative to the floor; while in the Radiosity method the surfaces in the environment are assumed to be perfect (or Lambertian) diffusers, reflectors, or emitters, which are assumed to reflect incident light in all directions with equal intensity. Therefore, the Split-Flux and Radiosity simulation method have limitations for windows with varying window positions.

The results also showed that when the floor visual reflectance was increased from 0.2 to 0.9, the lighting energy results from EnergyPlus+Radiance came closer to the results of EnergyPlus+Split-Flux/Radiosity and DOE-2.1e+Split-Flux simulations. Therefore, when the interior surfaces are bright, the lighting results using either Split-Flux, Radiosity or Radiance simulations are similar. It should be noted that the Split-Flux method only takes seconds to run an annual daylighting simulation versus Radiosity that can consump 0.2 minutes. However, Radiance needs around 5 minutes to run a medium accuracy annual daylighting simulation, which makes optimization studies different. Thus, EnergyPlus with Radiance simulation can be very timing consuming on the normal computuing hardware in an architectural office. Therefore, there is a need for an accurate tool that runs quickly. It can be useful to use a DOE-2/eQuest with Split-Flux for combined daylighting and thermal simulation when the interior surfaces are bright to save simulation time.

Finally, regarding the window location, the window located at the top or at the bottom of the exterial will give very different results than the window located at the center of the wall. As architecture code/standard regarding window design should not give the same credit for all window locations on façade.

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