SIMULATION OF DYNAMIC DAYLIGHTING AND GLARE CONTROL SYSTEMS FOR A SIX-STORY NET-ZERO ENERGY OFFICE BUILDING IN SEATTLE, WA

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ABSTRACT

As building owners and designers focus on meeting net-zero energy use, the realization of lighting power savings and a high-quality visual environment through the use of daylight becomes critical. Central to this effort is maintaining persistent visual comfort while meeting illuminance targets across variable sun angles and sky conditions. For these reasons, weather station controlled dynamic daylighting and glare control systems may provide the most persistent daylight performance in spaces where direct sunlight is present during large portions of the occupied times. Dynamic facade systems have the possibility of maintaining visual comfort while achieving maximum diffuse daylight performance over time. These systems also offer the possibility of being deployed when needed and retracting or reverting to a state of maximum visible light transmittance without user intervention when glare or unwanted direct sunlight is no longer present.

This paper presents simulation and analysis conducted by the University of Washington Integrated Design Lab (UW IDL) of short time-step luminance and illuminance performance of automated dynamic daylighting systems including an exterior venetian blind system and a variable transmittance electrochromic glazing system deployed in a planned net-zero office building in Seattle, WA.

BACKGROUND

Since the year 2000, the UW IDL has partnered with a regional energy efficiency organization, with utility funding, to support research and technical design assistance on new construction and major renovation projects in order to advance energy efficiency in the commercial building sector. Lighting in commercial buildings in the US consumes approximately 38% of site electricity and 20% of total site energy (EIA, 2009). For this reason, a substantial component of the UW IDL's work has been in the areas of lighting, daylighting, and building envelope technology.

Beginning in 2009, the UW IDL has provided technical assistance and simulation support for the design of a new six-story 54,000 square foot office building in Seattle, WA, seeking to meet the Living Building Challenge, a certification program developed by the International Living Futures Institute (ILFI, 2011). In order to meet the Challenge, the building must acheive multiple performance criteria including net-zero energy use. Given the urban site constraints, total available roof area, and the available solar resource, the annual energy use intensity (EUI) is limited to 18 kBtu/ft^2-yr (the annual expected production of the proposed photovoltaic array) to meet net-zero energy use.

A current Seattle Energy Code (2009) compliant office building is expected to have a lighting EUI of 11.25 kBtu/ft^2-yr (25% of the total building EUI at 45 kBtu/ft^2-yr) (Kakaley, 2011). Current whole-building energy simulations of the proposed net-zero design project an EUI of 16 kBtu/ft^2-yr, with lighting expected to be approximately 23% of site energy, or 3.7 kBtu/ft^2-yr, reflecting a 67% reduction in lighting power consumption over a code building. This is achieved by maintaining a connected lighting power density (LPD) of 0.4 W/ft^2, as well as through the use of photocell-controlled continuous dimming with complete shut off when daylight illuminance alone meets the ambient lighting criteria (350 lux) for a specified time period. Since lighting, including reductions for daylight-responsive controls, represents approximately 23% of the total building energy budget, the persistent delivery of sufficient, visually comfortable daylight illuminance and luminance is critical to meeting net-zero annual energy.

As indicated above, the significant inclusion of daylight in buildings holds tremendous potential to produce energy savings. However, lighting power savings are frequently under-realized, in large part due to building designs and patterns of occupant behavior that lead to blinds and roll-down fabric shades deployed in the "worst case scenario" position of blinds down and slats closed to maintain visual comfort. This essentially defeats the daylighting design intent. Manual systems of glare and solar shading can be very effective if properly used, however, they rely on continuous user attention to maintain complete glare control while achieving maximum daylight performance. A 2005 report on sidelighting (daylight illuminance from vertical windows) and photo controlled electric lighting systems produced by the Heschong Mahone Group (HMG, 2005) identified blind use by building occupants as a significant contributor to low realized lighting power savings ratios relative to potential conservation from daylight. In overcast sky dominated climates such as Seattle, reductions in daylight performance from unnecessary blinds deployment can be particularly pronounced. This is because blinds, shades, and fixed shading devices can reduce daylight performance in the overcast by as much as 80%. This is similarly the case when blinds are deployed when no direct beam sunlight is present (e.g. a west facade at 9 am). For these reasons we recommend automated dynamic facade systems that enable light diffusion, glare control, and solar shading when required, and revert to maximum unobstructed aperture area under overcast or clear sky conditions without direct sun. Such systems are intended to maximize daylighting performance in the overcast while providing complete sun control. This affords designers greater predictability and confidence in meeting energy performance targets, and reducing other building system sizes commensurate with expected solar shading and lighting power reductions.

Methods exist for simulating the annual illuminance performance of dynamic facade systems including the software programs Daysim, COMFEN, and others, however, limited resources are available to simultaneously understand luminance distributions, illuminance, and the visual character of interior volumes under typical operations of dynamic facade systems over time. This paper presents efforts to quantify these variables in a net-zero energy office building using animated short time-step luminance and illuminance simulations of a fourth-floor open office area with southeast, west and northwest facing glazing.

BASIS OF DESIGN

The design intent is to provide daylight as the primary source of ambient illumination at the test office, in Seattle, WA. As part of this effort our intention is to provide continuous visual comfort (i.e., no direct line of sight to the disc of the sun, and minimal luminance values exceeding 2000 cd/m2) without sacrificing daylighting performance. Through simulation it has been determined that most of the interior office workstations will be subject to low-angle direct sunlight throughout the year without the presence of some type of shading system. Two dynamic facade systems (automated exterior venetian blinds and a variable transmittance electrochromic window (ECW) glazing system) have been analyzed in an effort to meet key daylighting objectives.

1. Exterior Automated Venetian Blinds

Objectives for the automated venetian blinds are as follows: (1) to block direct solar radiation outside the building envelope; (2) to control glare by ensuring that no direct sunlight enters the office during times when occupants are present and that no line-of-sight exists between regularly occupied critical visual task areas and the disc of the sun; (3) to redirect diffuse daylight to the ceiling and other interior surfaces; (4) to retract, without user intervention, during periods when no direct sunlight is present or under overcast sky conditions.

The simulated exterior automated venetian blinds are based on a commercially available 100mm (4”) slat system with a reflectance value of approximately 50%. Blinds retraction and slat angle control is provided via a single tilt motor and a lift motor within the blind head rail. The operational intent is that the blinds be deployed at the minimum slat angle required to just block direct sunlight continuously on an annual basis, and to be retracted whenever possible to preserve daylight and views. It is intended that blind deployment and slat angles be controlled by a combination of the astronomical time clock and weather station data (clear skies vs. overcast), as well as by other factors (i.e. wind, temperature, etc.) recommended by the manufacturer. It is also intended that under partly cloudy skies, once blinds are deployed that they remain in clear sky deployment mode for a specified time period regardless of sky condition to avoid excessive cycling.

2. Automated Variable Transmittance Electrochromic (ECW) Glazing System

The objectives for the variable transmittance ECW glazing system differ slightly from that of the automated exterior blinds, due to the fact that with this system sunlight is not blocked or redirect, but transmittance is reduced. Objectives for the ECW glazing system are: (1) to maximize the use of diffuse daylight at prescribed target levels; (2) to control glare by reducing the transmittance of direct sunlight and glare caused by the disc of the sun; (3) revert to a state of maximum transmittance, during periods when no direct sunlight is present or under overcast sky conditions.

The simulated variable transmittance glazing is based on a system with maximum visible light transmission of 70% (0.70 Tvis) and a minimum of 3% (0.03 Tvis), with an intermediate state only during change over. They are deployed per exterior sensor based on the presence of direct beam sunlight on the window surface. In addition, exterior weather station data and astronomical time clock, can allow for supplementary controls to be set, in an effort to maximize building daylighting and energy performance. It is our intent that the variable transmittance glazing system be deployed only when direct sunlight is present on an annual basis, and be switched to normal transparent state glazing whenever possible to allow for unimpeded diffuse daylight and views.

SIMULATION PROCESS

1. Model Description

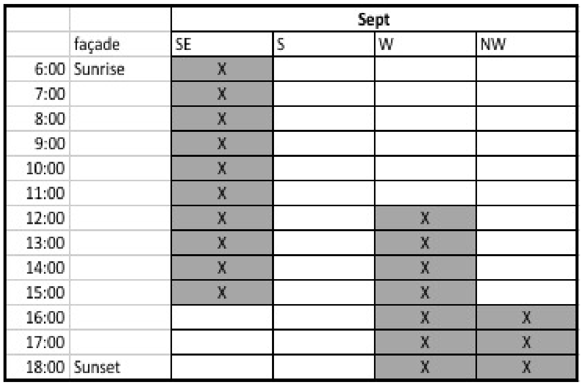
Using the building simulation program Ecotect Analysis, a digital model based on the geometry of the proposed six-story, 54,000 square foot test office was created to serve as the platform for simulation. Adjacent building massing was included based on current conditions at the building site. Effort was taken to assign material reflectance values based on the physical properties of the proposed interior and exterior materials. In this case, walls are specified with a reflectance value of approximately 55%, floors 20%, and the ceiling “clouds” 80%. Double glazed, low E glass with a transmittance of 70% was assigned for all glazing, and window head, jamb, sill and mullions were modeled to account for the proposed window geometry and wall thickness. A furniture layout created for a prospective tenant for the fourth floor office space was used to select the location of regularly occupied task areas and areas for primary visual field analysis.

Fig 1. Rendering of test office (Image: The Miller Hull partnership).

2. Deployment Schedule Development

To simulate the performance of each dynamic facade system, a schedule for deployment was generated based on sun position in Seattle, WA relative to proposed building facade orientation and overshadowing from adjacent structures. Simulation schedules were developed for the summer and winter solstices and autumnal equinox. In an effort to maximize daylighting performance while maintaining occupant visual comfort, each schedule was determined per direct beam sunlight on a window-by-window basis. If direct sunlight was present the system was deployed, and when no longer present, the system was retracted.

Short time step illuminance and luminance simulations (from sunrise to sunset in 15-minute increments) were generated based on the schedules developed for each system. Both follow the prescribed deployment rules (as outlined above), however, an additional slat angle schedule for the exterior venetian blinds had to be established. Slat angles were set at the minimum angle (0°, 22.5°, or 45° to the horizontal) required to block line of sight to the disc of the sun. Baseline simulations were also produced to show unimpeded direct sunlight conditions following the same timeline as the dynamic daylighting and glare control systems simulations (sunrise to sunset in 15-minute increments).



		Sept			
	façade	SE	S	W	NW
6:00	Sunrise	X			
7:00		X			
8:00		X			
9:00		X			
10:00		X			
11:00		X			
12:00		X		X	
13:00		X		X	
14:00		X		X	
15:00		X		X	
16:00				X	X
17:00				X	X
18:00	Sunset			X	X

Fig 2. Hourly deployment schedule of electrochromic window glazing deployment by facade, per direct beam sunlight exposure at the fourth floor of the test office in Seattle, WA. From 13;00 until 15:00 direct sun is present on both the southeast (SSE) façade and the west façade.

3. Simulations

Since both daylight illuminance performance and visual comfort were analyzed for the test office, illuminance and luminance data was calculated. For this reason each sky condition and time of year required two simulations each following different processes. Our methods for generating illuminance and luminance data is outlined below, as well as the process of compiling each simulation into an animation and graph.

a. Daylight Illuminance Simulation

A calculation grid with points spaced at 5’-0” (1.52 m) each way corresponding to the geometry of the fourth floor of the test office, was generated using Ecotect Analysis for measuring illuminance. For each 15-minute time step, a simulation was exported to Radiance Synthetic Imaging software (Ward, 2003). Due the volume of simulations to be generated, simulations were batched in an effort to save time. In September alone, 54 simulations were created to cover sunrise to sunset. Each individual simulation was started in Radiance to generate its corresponding files. Once initial files were generated, the individual simulations could be stopped, and then combined into a batch run. Results were imported back to Ecotect and a comma separated value data (CSV) file of illuminance values and a “screenshot” of each isolux contour map was saved in jpeg image format.

b. Daylight Luminance Simulation

Luminance simulations were also generated using Ecotect Analysis and the Radiance Control Panel (Marsh, 2005). From Ecotect, a Radiance scene file was created for each geometric or material modification. For example, in the September simulation of automated blinds, nine Radiance scene files were created to account for the slat geometry changing throughout the day (Fig. 4). All simulations corresponding to a Radiance scene (simulations with the same geometric and material definitions) were batch rendered. The resulting high dynamic range (HDR) images were imported back to the Radiance Control Panel for image processing. Here a standard luminance scale (0 – 2500 cd/m^2) was set and false color luminance maps were generated (Fig. 8). Finally, to compile the luminance maps into an animation, the files were batch converted to the jpeg image format.

c. Compiling Simulated Data

All resulting jpeg images, both illuminance and luminance, were assembled into animations using a commercially available animation compiler. These simulations allowed us to visualize the dynamic effects of each system in terms of both illuminance and luminance distribution throughout the space and visually evaluate the dynamic systems during specific time periods. In addition to the animated simulations, illuminance data, collected from proposed photocell locations (Fig. 3), was graphed to analyze the daylighting performance of each system.

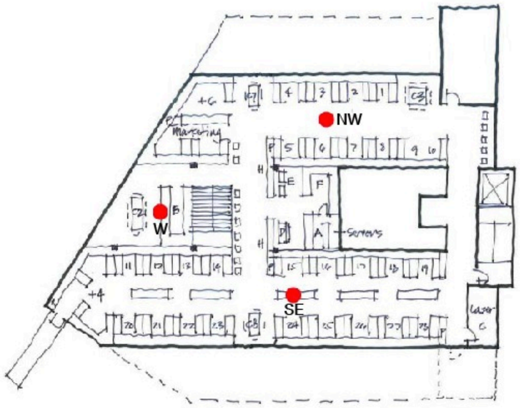
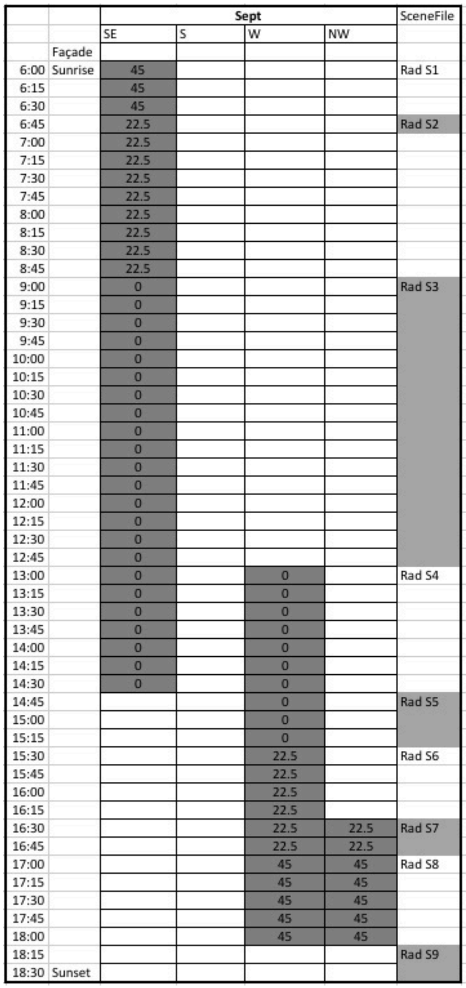


Fig 3. Potential photocell locations for southeast, west and northwest lighting zones / representative points of illuminance data collection for graphs.



		Sept				SceneFile
		SE	S	W	NW	
	Façade					
6:00	Sunrise	45				Rad S1
6:15		45				
6:30		45				
6:45		22.5				Rad S2
7:00		22.5				
7:15		22.5				
7:30		22.5				
7:45		22.5				
8:00		22.5				
8:15		22.5				
8:30		22.5				
8:45		22.5				
9:00		0				Rad S3
9:15		0				
9:30		0				
9:45		0				
10:00		0				
10:15		0				
10:30		0				
10:45		0				
11:00		0				
11:15		0				
11:30		0				
11:45		0				
12:00		0				
12:15		0				
12:30		0				
12:45		0				
13:00		0		0		Rad S4
13:15		0		0		
13:30		0		0		
13:45		0		0		
14:00		0		0		
14:15		0		0		
14:30		0		0		
14:45				0		Rad S5
15:00				0		
15:15				0		
15:30				22.5		Rad S6
15:45				22.5		
16:00				22.5		
16:15				22.5		
16:30				22.5	22.5	Rad S7
16:45				22.5	22.5	
17:00				45	45	Rad S8
17:15				45	45	
17:30				45	45	
17:45				45	45	
18:00				45	45	
18:15						Rad S9
18:30	Sunset					

Fig 4. Deployment schedule of automated exterior venetian blinds for September 21 clear skies with corresponding Radiance scene file. South glass shaded by a fixed vertically mounted PV panel array.

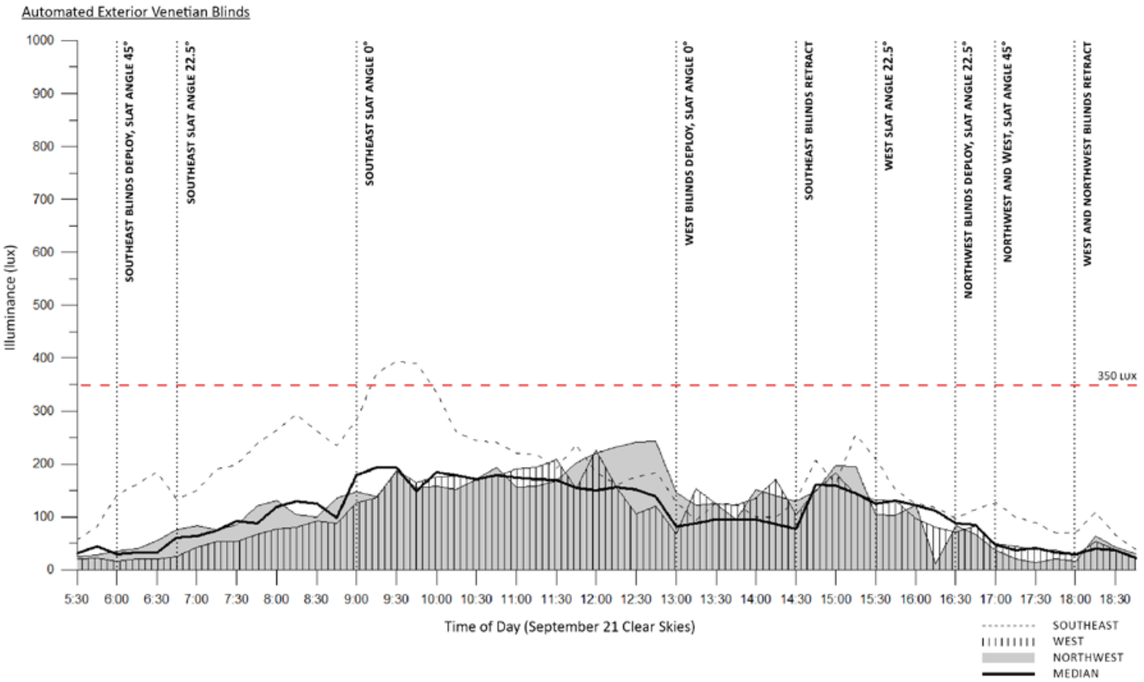


Fig 5. Daylight illuminance at photocell location with automated exterior venetian blind system on September 21, clear sky (by facade).

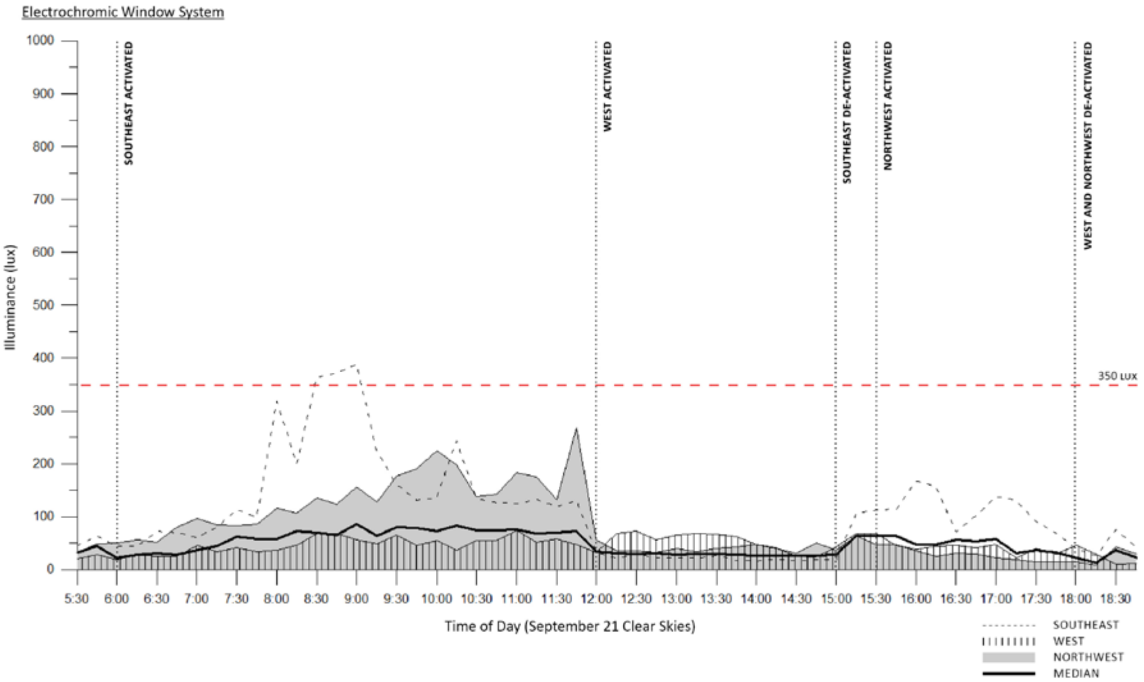


Fig 6. Daylight illuminance at photocell location with electrochromic window system on September 21, clear sky (by facade).

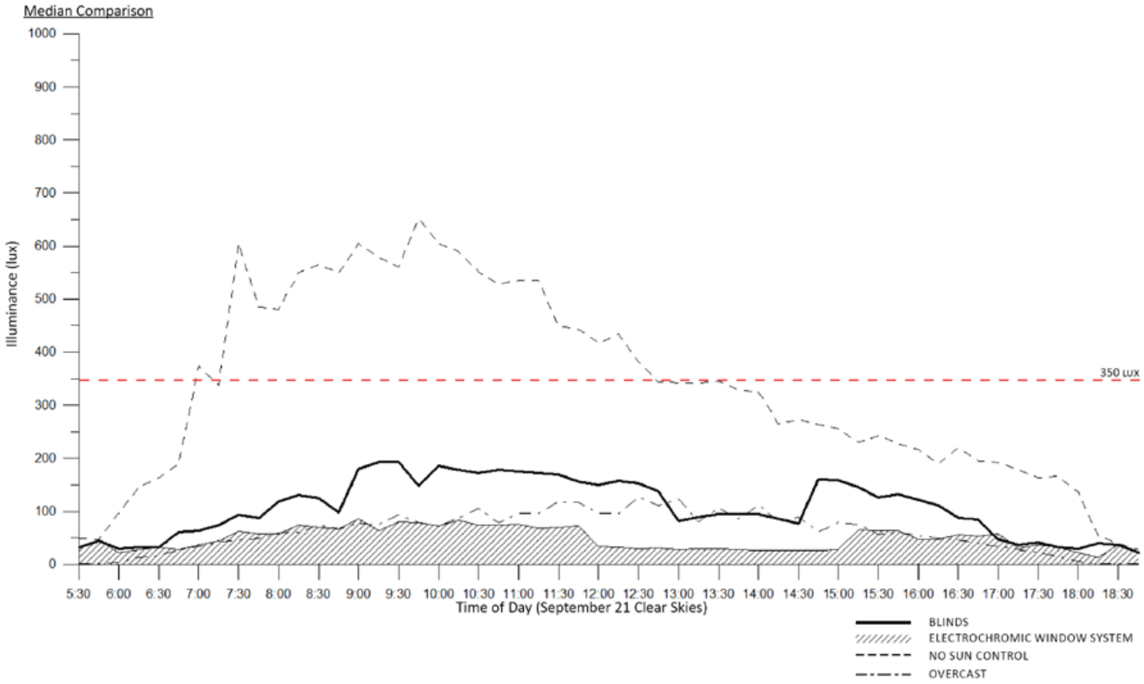


Fig 7. Median horizontal illuminance levels for the entire office floor area for September 21, clear sky.

RESULTS

1. Daylight Illuminance Results

350 lux was established as a target ambient illuminance level for visual task areas in the office.
To show the performance of all systems relative to a baseline of un-shaded direct beam sunlight or unobstructed overcast sky illuminance we present median daylight illuminance over the entire occupied floor plate (fig. 7) for 21 September. This illustrates the degree to which each scenario reduces ambient illuminance (over unobstructed direct sunlight) when deployed; and the degree to which illuminance levels remain consistent throughout the day under the proposed deployment schedule. As expected ambient illumination levels are reduced when any shading system is deployed. This is particularly pronounced when two major facades are in direct sunlight simultaneously. For example, in the test office from 12 pm until sunset, shading systems are deployed at the southeast and west, then the west and northwest, resulting in marginal daylighting performance during those time periods.

In perimeter office areas when using blinds to controls glare on a clear September day, daylight meets roughly 50% of the ambient illumination requirements during the primary occupancy time of 8am through 5pm (fig. 5.). During the same period the ECW system meets about 25% of ambient lighting criteria. Illuminance levels are particularly reduced when the ECW system is deployed on both the southeast and west facade. During these times (between noon and 3pm) ECW system is substantially compromised delivering less than 100 lux of ambient illumination (fig. 6.).

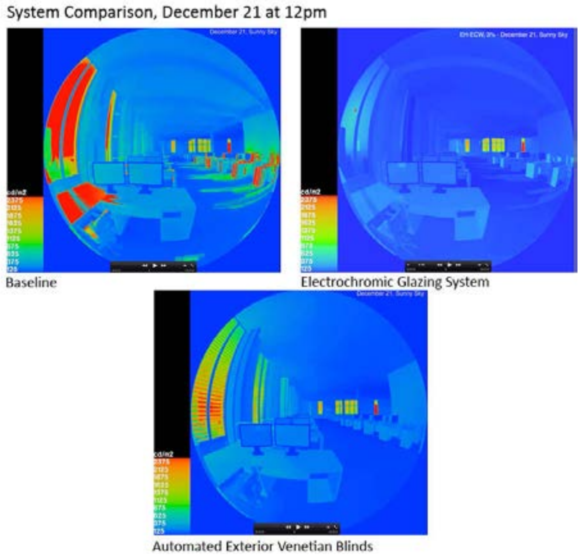


Fig 8. Luminance comparison of dynamic facade systems and a baseline simulation with no shading controls on December 21 at 12 pm

2. Daylight Luminance Results

Automated deployment of exterior blinds and ECW glazing are both successful at eliminating high luminance levels on interior work surfaces within the primary visual field at the test location (a desk at the southeast facade facing south. However, with the ECW system, the potential still exists for occupants to be affected by glare where views to the exterior include the path of the solar disc. Potential glare, as indicated by the red and orange areas of the false color luminance maps (fig. 8), using indices of 2000-2500+ cd/m^2 indicate areas in each scenario where excessive brightness may pose visual comfort problems.

DISCUSSION

1. Simulation Methods

The creation of short time-step animated luminance maps offer a "snapshot" of the daylight performance of a space over a limited time period and sky condition. This data enables designers and owners to conduct visualization of daylight distribution and the visual character of dynamic daylight systems as they operate within an interior volume. This type of data is complimentary to annualized TMY (typical meteorological year) weather data-based metrics such as Daylight Autonomy (DA) which evaluate the percentage of time a point reaches a specified illuminance threshold (Reinhart, et al. 2006). By evaluating a range of instantaneous luminance measurements within a temporal context, designers can gain a greater understanding of the visual character of their daylighting designs by evaluating distributional quality across key time points and transitions (e.g. blinds deployments, photo-control response, changes in sky conditions, daytime to nighttime scene, etc.). Specific characteristics can be visually correlated between daylight luminance distribution and primary architectural elements such as windows, walls, and visual task areas as well as other design considerations such as views to the exterior. Such simulations are crucial for ensuring occupant comfort and the integrity of design intent.

As dynamic shading becomes an increasingly common as a tool for maximizing daylighting performance and increasing building energy performance, animated luminance maps can serve to give designers the tools to evaluate design options and to develop the most appropriate sequence of operations for dynamic daylighting and glare control systems.

Currently, the process used to generate animated luminance maps for dynamic shading systems is often beyond the time and technical resources of most building designers. Future work will identify methods for automated scheduling of multiple Radiance scene files and batch render processes for rapid compiling of animated scaled false color luminance maps. The quantitative analysis of such animated sequences could provide a basis for describing distributional variations of luminance relative to a defined baseline condition.

2. Technical Conclusions

In terms of ambient illuminance, the automated exterior blinds deliver more horizontal illuminance than ECW system, this is most likely due to the light redirecting nature of the blinds system in lieu of a absolute reduction in overall light transmissions of the apertures. However, unlike the blinds, the ECWs provide nearly continuous unobstructed views to the exterior, though for this reason they do not provide complete occlusion of the disc of the sun.

Each of the characteristics inherent to these technologies can be optimized through building design to best suit two of the key roles windows are intended to play in building interiors: to provide diffuse daylight and to provide views to the exterior environment. Preliminary findings point to the combination of ECW glazing with opaque, diffuse, or other optically robust mechanisms for light redirection where glazing is optimized for delivering a prescribed diffuse distribution and range of interior illuminance. Such a system would enable combined light redirection/scattering and intensity control as well as solar heat gain control. This would be especially beneficial at locations where moveable exterior shading devices are not feasible.

In "view" glazing, ECWs, especially where intermediate states of darkening are possible, enable a much finer degree of luminance control in views to the exterior while maintaining a completely unobstructed view. This offers the potential for blinds or roll-down fabric shades to be deployed less frequently in view windows and therefore may increase visual comfort and interior illuminance. With both the exterior venetian blinds and the ECW systems, sky brightness immediately after system retraction indicates the potential for glare. This suggests deployment schedule modifications to include account for sky brightness surrounding the solar disc.

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REFERENCES

Apte, J.S., D.K. Arasteh. (2006). Window-Related Energy Consumption in the US Residential and Commercial Building Stock. Lawrence Berkeley National Laboratory. LBNL-60146. http://gaia.lbl.gov/btech/papers/60146.pdf

Autodesk - Autodesk Ecotect Analysis. (n.d.). . Retrieved February 22, 2011, from http://usa.autodesk.com/adsk/servlet/pc/index?id=12602821&siteID=123112

COMFEN 4.0. (2011). Windows and Daylighting Group, Building Technology Department, Lawrence Berkeley National Labs. http://windows.lbl.gov/software/comfen/comfen.html, Retrieved October 15, 2011

Heschong, L., (2005). *Sidelighting Photocontrols Field Study;* Southern California Edison, Pacific Gas and Electric, Northwest Energy Efficiency Alliance, Technical Report.

International Living Future Institute (ILFI). (2010). *Living Building Challenge Version 2.0*. https://ilbi.org/lbc/standard , Retrieved October 15, 2011

PAE Consulting Engineers, Portland, OR. www.pae-engineers.com

Reinhart, C. F., Mardaljevic, J., & Rogers, Z. (2006). “Dynamic Daylight Performance Metrics for Sustainable Building Design,” *Leukos*, 3 no.1,: 7-31.

Marsh, A. (2005). The Radiance Control Panel, Square One Research.

The Miller Hull Partnership. Seattle, WA. www.millerhull.com

U.S. Energy Information Administration (EIA). (2009). Lighting In Commercial Buildings; US DOE. Retrieved October 6, 2011 from http://www.eia.gov/emeu/cbecs/cbecs2003/lighting/lighting1.html

Ward, G. (2003). The RADIANCE 3.5 Synthetic Imaging System. Retrieved February 22, 2010 from http://radsite.lbl.gov/radiance/refer/ray.html