Title

Discomfort glare with complex fenestration systems and the impact on energy use when using daylighting control:

Authors
Hoffmann, Sabine
McNeil, Andrew
Lee, Eleanor S.
et al.

Publication Date
2015-11-03

Ernest Orlando Lawrence
Berkeley National Laboratory

Discomfort glare with complex fenestration systems and the impact on energy use when using daylighting control

Sabine Hoffmann, Andrew McNeil, Eleanor S. Lee, Raghuram Kalyanam

Energy Technologies Area

November 2015

Proceedings of the 10th International Conference on Advanced Building Skins, Congress Center of Bern Expo, Bern, Switzerland, November 3-4, 2015

Disclaimer

Acknowledgment

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231 and by the California Energy Commission through its Public Interest Energy Research (PIER) Program on behalf of the citizens of California.

Completion of the paper was supported through the research center High Performance Composite Constructions, HiPerCon, at University of Kaiserslautern.

Discomfort glare with complex fenestration systems and the impact on energy use when using daylighting control

Sabine Hoffmann[1], Andrew McNeil[2], Eleanor Lee[2], Raghuram Kalyanam[1]

[1] University of Kaiserslautern, Department of Civil Engineering, Chair of Facilities Engineering, Paul-Ehrlich-Str. 14, 67663 Kaiserslautern, Germany
Corresponding author: Sabine.Hoffmann@bauing.uni-kl.de

[2] Building Technologies and Urban Systems Division, Energy Technologies Area, Lawrence Berkeley National Laboratory, Mailstop 90-3111, 1 Cyclotron Road, Berkeley, California, 94720 USA

Abstract

Glare is a frequent issue in highly glazed buildings. A modelling approach is presented that uses discomfort glare probability and discomfort glare index as metrics to determine occupants' behaviour. A glare control algorithm that actuated an interior shade for glare protection based on the predicted perception was implemented in a building simulation program. A reference case with a state-of-the-art base glazing was compared to the same glazing but with five different complex fenestration systems, i.e., exterior shades. The windows with exterior shades showed significant variations in glare frequencies.

Energy use intensity in a prototypical office building with daylighting controls was greatly influenced for the systems with frequent glare occurrence. While the base glazing could benefit from glare control, some of the exterior shades showed significantly greater energy use when discomfort glare-based operation of interior shades was considered.

Keywords: Complex fenestration systems, discomfort glare, daylighting control, Radiance, building simulation, energy use intensity

1. Introduction

Thermal and visual discomfort in office buildings impairs employees' ability to focus on their actual tasks. Complex fenestration systems (CFS), in particular exterior shades, reduce solar load and daylight availability in the room, direct radiation on the occupant. and discomfort glare at workstations. Quantifying these effects through modeling and simulation remains a challenging task due to the three-dimensional and transient nature of the problem. Obviously, solar load and the use of CFS not only impact comfort of occupants but also strongly affect energy use. Integrating occupants' behavior due to discomfort into the whole building energy model is necessary, especially when daylighting controls are used to achieve maximum energy savings.

In the first part we describe results from assessing discomfort glare based on Radiance calculations applying two commonly used indices, daylight glare index (DGI) and daylight glare probability (DGP), to a standard open space office situation. In the second part we present results from building energy simulation with Energy Plus where a realistic scenario of interior shade operation provided manual glare control. When deployed, the interior shade reduced interior daylight illuminance and window loads, affecting both simulated lighting energy use when daylighting controls were used and HVAC energy use.

2. Methodology

The following results are based on extensive research and development of various simulation tools at the Lawrence Berkeley National Laboratory, which have been used for large parametric studies in the past. A detailed description of the assumptions for the thermal building model and the CFS can be found in previous publications [1,2]. We decided to keep the names of the CFS the same as in the references, but reduced the number of systems shown here. In addition to a brief overview of the used simulation methods and complex fenestration systems, we focus on the assessment of discomfort glare in the simulation.

2.1 Simulation tools

Various simulation tools were used for this study and combined in a workflow that is shown in Fig. 1. GenBSDF based on Radiance simulation results [3] was used to create a bi-directional scattering distribution function (BSDF) for the shading system. This BSDF was imported into the Window 7 shading library [4] and added to the base glazing system, which itself is based on data from the International Glazing Database (IGDB) [5]. Radiance calculates the solar energy incident on the fenestration layers (shades, glass layers) and on the interior surfaces of the room, and the lighting energy that is necessary to maintain a target work place illuminance. Window 7 exports a BSDF of the CFS (shade + base glazing). These inputs are used in EnergyPlus [6] to calculate the window and room heat balance and resultant energy use intensity (EUI) of a prototypical building. The workflow also uses pre-calculated values for discomfort glare (see Sections 2.3-2.5), which operates an interior shade for glare control based on a user-defined algorithm.

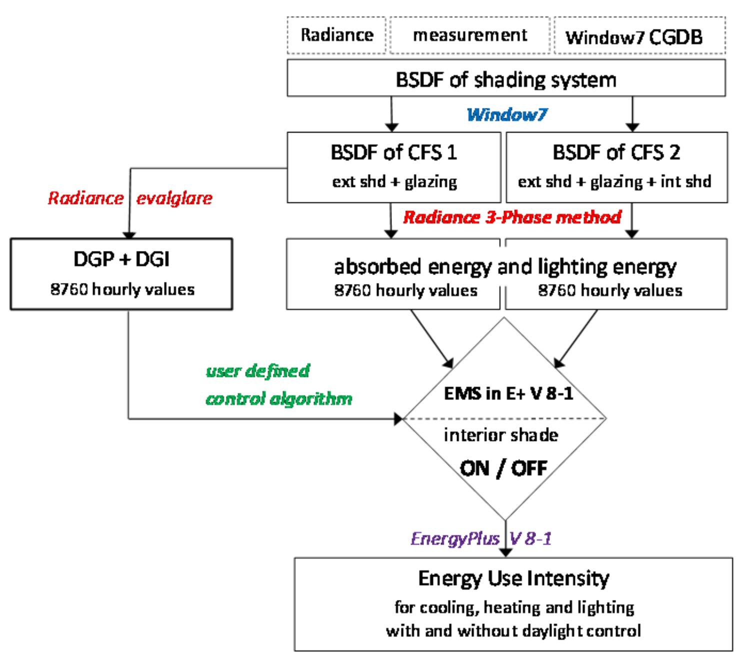

Figure 1: Workflow using various simulation tools

2.2 The reference base glazing and the complex fenestration systems

The base glazing system is defined as an argon-filled dual-pane window with an outboard layer of low-iron glass, a low-e coating (e = 0.018) on surface two that is spectrally selective, and an inboard layer of clear glass (system thickness: 24 mm). The performance values of the base glazing can be found in Table 1.

The range of modeled exterior shading systems comprises two slat shading systems (shd 1, shd 2), two external roller shades (shd 6, shd 7a) and an aluminum louver (shd 8). All systems were modeled without mounts or anchors, with no connection to the window and at a fixed distance to the outer glass layer, which is representative for the class of system. All systems were modeled as always lowered, no automation of height was considered even for the retractable shades. The performance values of the exterior shading systems can be found in Table 1. The geometry of the exterior shades is shown in Fig. 2.

	U-value (NFRC) [W/m^{2}K] COG	**Solar Heat Gain Coefficient**	**Visible Trans-mittance T_{vis}**	**Visible Reflectance R_{vis}**	**Solar Reflectance R_{sol}**	**Solar cut-off angle [deg]**
base glaz.	1.4	0.30	0.65	0.08/0.06 (front/back)	0.51/0.56 (front/back)	-
shd 1	1.1	0.31	0.63	0.50*	0.50*	42
shd 2	1.1	0.18	0.34	0.50*	0.50*	29
shd 6	1.0	0.08	0.12	0.60*	0.55*	19
shd 7a	1.0	0.10	0.18	0.87*	0.93*	30
shd 8	1.1	0.14	0.27	0.70*	0.70*	30

Table1: Performance values (National Fenestration Rating Council - NFRC) for base glazing and CFS based on Window7 calculations. All values are for the center of glass (COG). (material reflectivity)*

Shd 1 and 2 are variations of a commercial window screen product [7] that is mainly used in retrofit projects. They attach to the frame or to a separate support, and are usually mounted close to the window although it could be used at a greater distance to the façade as well. The screens are slat shading systems at a micro scale. Shd 6 is an external roller shade made of stainless steel that rolls up into a casing on the window head powered by an electric motor [8]. The special shape of shd 6 leads to a solar cut-off angle of 19°. Shd 7a is a retractable exterior shade including casing and guardrails with the additional option of adjusting the slat angle either manually or automated [9]. Shd 7a has a highly reflective finish.

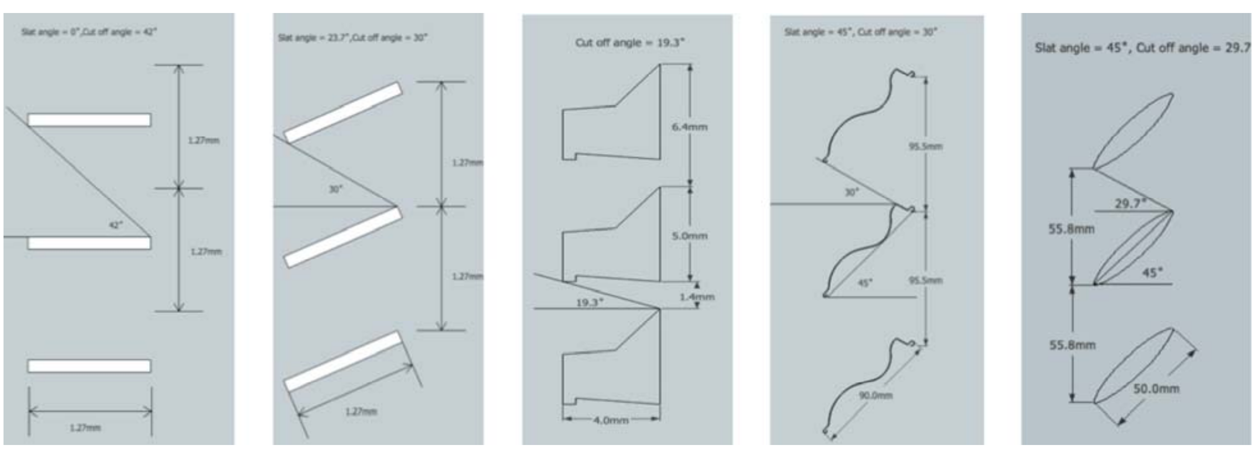

Figure 2: Geometry of the exterior shades

2.3 The Radiance glare simulation

We evaluated glare with Radiance using a model of an open plan office space. The model measured 12.2 m wide by 14.0 m deep, with a floor-to-ceiling height of 2.7 m. The office model contained cubical partitions creating desk spaces that were 2.4 m wide and 3.1 m deep. Partitions were 1.0 m tall parallel to the window and 1.4 m tall perpendicular to the window. Each cubical contains an L- shaped desk with a height of 0.76 m as well as desk chairs and cabinets. A rendering of the space is shown in Fig. 3.

We generated hourly renderings using the Radiance three-phase method, which allows efficient annual daylight simulation of complex fenestration systems [10, 11] and was validated by McNeil and Lee [12]. Renderings were created for nine views total, from four viewpoints (see Fig. 3).

The rendered images were processed with evalglare [13] to derive glare metrics.

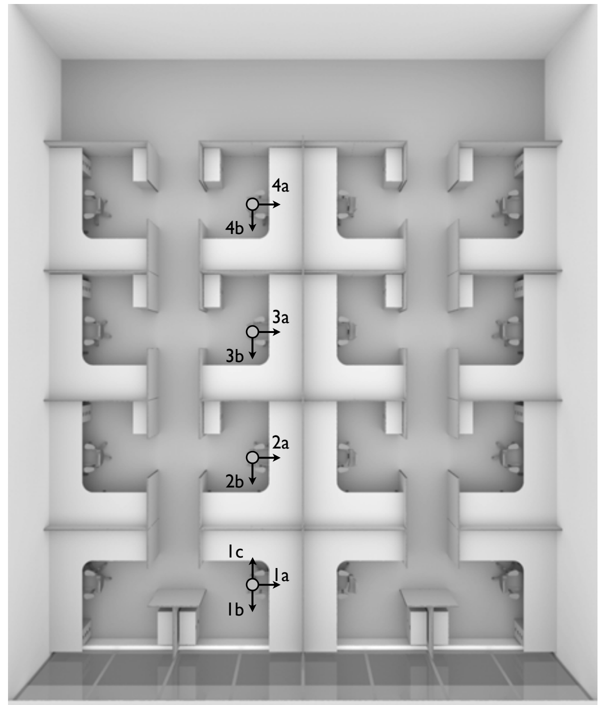

Figure 3: Top view of the model used for glare simulation with viewpoints and view directions indicated by arrows.

2.4 Discomfort glare metrics

2.4.1 Daylight glare index (DGI)

The Daylight glare index is a modification of the British glare index also known as Cornell equation, and was adapted to predict glare from a large source (window). Several experiments using fluorescent lamps behind an opal-diffusing screen contributed to the development of this equation. The equation is expressed as follows:

$$DGI = 10 \times \log_{10} 0.48 \sum_{i=1}^{n} \frac{L_{s,i}^{1.6} \omega_{pos\, s,i}^{0.8}}{L_b + (0.07 \omega_{s,i}^{0.5} L_{s,i})}$$

DGI considers the source luminance, its size and its position in the field of view and correlates it against the background luminance. Additional eye adjustment to the visible luminance is compensated by a small percentage of the source luminance. This results in identifying the threshold values of ‘intolerable glare’ and ‘barely perceptible glare’ at 31 and 18 respectively [14, 15].

2.4.2 Daylight glare probability (DGP)

DGP considers direct sunlight and some specular reflections as glare sources which are common in a workspace. The equation is expressed as follows:

$$DGP = 5.87 \times 10^{-5} E_v + 9.18 \times 10^{-5} \log_{10} 2 \left(1 + \sum_{i=1}^{n} \frac{L_{si}^2 \omega_{s,i}}{E_v^{1.87} P_i^2}\right)$$

The first term of the DGP equation uses vertical eye illuminance (Ev) as its sole input, which can lead to predictions of discomfort glare in exceedingly bright scenes even without significant visual contrast. The latter-half of the equation uses the familiar comparison of the source luminance and size against the scene luminance and the position index of the glare source, an evaluation of visual contrast. In this sense, DGP is the evaluation of glare, which considers the most factors that contribute to discomfort. A glare probability greater than 0.45 corresponds to intolerable glare – an estimated 45% of people would feel discomfort in such a lighting situation, while a value less than 0.3 is considered imperceptible glare [15].

2.5 Glare control

To assess the impact of glare control on the energy use intensity, a “manual” glare control was modeled in Section 4. “Manual” glare control means that whenever a discomfort glare condition occurred for any of the viewpoints shown in Fig. 3, an employee would fully lower an interior shade, which then remained lowered until the end of the workday (8 pm). An indoor, light gray (R_{sol} = 0.75) fabric roller shade with an openness factor of 3 % and diffusing properties was modeled as the interior shade.

In the simulation, the manual glare control was actuated based on the Radiance results for DGP and DGI. The space was modeled with an electric lighting system that dimmed according to daylight availability so as to provide a target illuminance of 500 lux.

As numerical limit when an interior shade had to be deployed because of glare, values of DGP ≥ 0.38 (0.38 corresponds to perceptible glare) or DGI ≥ 24 (24 corresponds to just uncomfortable) for any of the viewpoints were chosen. At or above these values we assumed glare to be perceptible by the occupants leading to discomfort and hence to the lowering of the interior shade.

3. Glare occurrence

When looking at discomfort glare, the frequency and the time of occurrence is of great interest. The following carpet plots (Fig. 4 and 5) show results for a window-to-wall ratio of 60 %.

3.1 Glare occurrence with base glazing

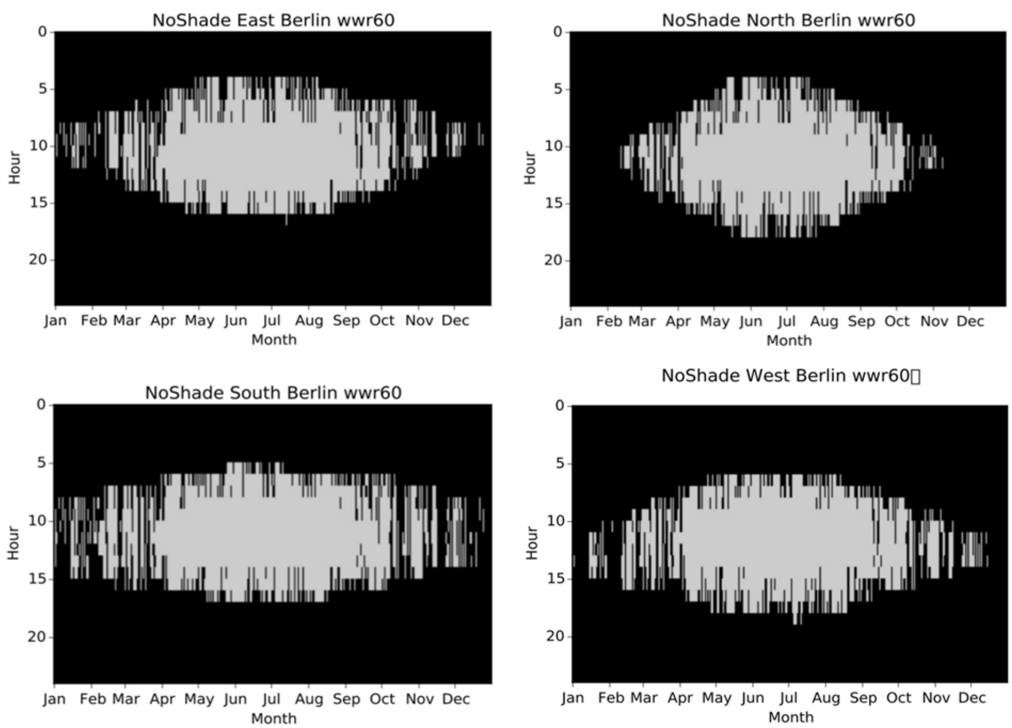

Figure 4: Glare occurrence for the base glazing, 4 orientations, Berlin climate, Standard Time.

The white area in Fig. 4 indicates the hours at which the discomfort glare condition described in Section 2.5 was fulfilled for at least one viewpoint over the months of a year (x-axis) and over the hours of a day (y-axis). Each graph indicates a different orientation (East, North, South, West). With the base glazing only (i.e. no exterior shade), overall glare frequency is high. We observe glare conditions frequently during morning and evening hours in summer. Differences between east and west are rather small and glare appears to be due to both, diffuse radiation and direct sunlight, as one can observe glare during evening hours in the east and during morning hours in the west.

3.2 Glare occurrence with exterior shade (shd 2)

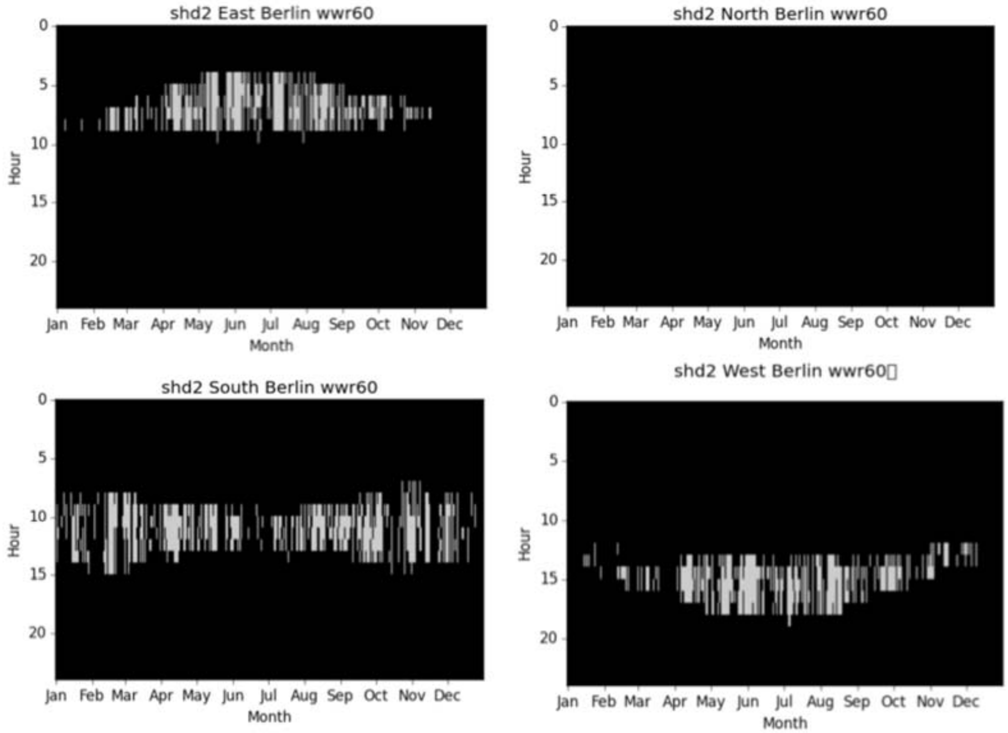

Figure 5: Glare occurrence for shd 2, 4 orientations, Berlin climate, Standard Time.

Fig. 5 shows the occurrence of glare when an exterior shade (shd 2) is used. With the exterior shade, glare only occurs when direct sunlight hits the facade. There is no glare in the north oriented office room as it does not experience direct radiation. In the east oriented office room there are glare conditions in the morning while in the west oriented room there are glare conditions in the evening. Glare occurrence in the south oriented room happens more frequently in early spring and late fall when the incidence angle is small due to low solar altitude and the intensity high. At the highest altitude angles around summer solstice, glare is almost negligible in a south oriented room.

3.3 Comparison of different shades

The comparison between the base glazing without shade and shd 2 showed significant differences in glare pattern as well as a strong correlation of glare with direct radiation in case of the exterior shade. Fig. 6 compares five different exterior shades in terms of accumulated daily glare hours over a year in 2 hours brackets from 8 am to 6 pm. It shows that the base glazing (red) and also shd 1 (green) produce glare conditions over the whole course of the day (greater prevalence of glare from the sky), while shd 2, 6, 7a and 8 are clearly related to direct radiation. However, the base glazing and shd 1 seem to be influenced by direct radiation as well since their peaks are shifted towards the morning for east orientation, towards the afternoon for west orientation while they are symmetrical on the north and south façade. Overall the number of hours with glare conditions are high for the base glazing without shade and shd 1, with 2200 hours of glare for the base glazing on the west façade and 1865 hours of glare for shd 1. This represents 88 % (no shade) and 74 % (shd 1) of the overall office time.

Between shd 2, shd 6, shd 7a and shd 8 there are significant differences in absolute numbers of glare with shd 6 being the best performing shade with almost no glare condition. Shd 7a and shd 8 produce significantly less frequent glare conditions (14% and 19% of year) than shd 2 (30% of year) for the most critical situations.

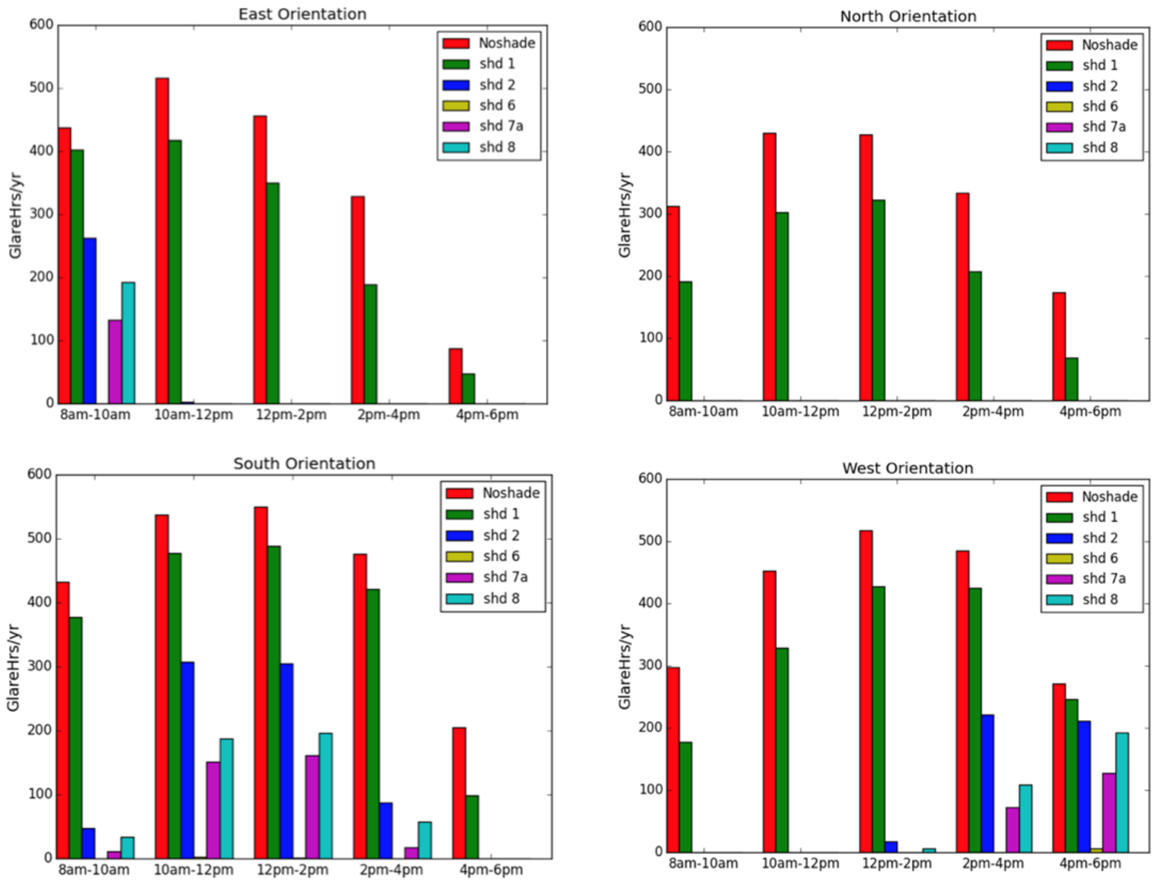

Figure 6: Glare occurrence for various shades and the base glazing

4. Impact on energy use

Discomfort glare impacts not only occupants' satisfaction but also energy use, especially when daylighting controls are used and people operate interior shades to block daylight. The modeled office space is a large office building with significant internal loads. Window-to-wall ratio (WWR) was varied from 0 % (fully opaque façade) to 60 % in 15 % increments. There were office rooms located at all four cardinal directions. The building envelope matches California Title 24 2013 standards, but may not correspond to current EU regulations for new construction. For the detailed building model description please refer to [1,2].

The following Figures 7 and 8 show the energy use intensity (EUI) as source energy (conversion factor of 1.1 for gas and 3.3 for electricity) for the modeled office building. Energy is provided by a variable air volume system. EUI comprises 1) energy for the cooling and (gas powered) heating coils of the central unit, 2) energy used by the reheat coils at the VAV boxes and 3) fan energy to distribute air from the central unit to the zones. Energy use from the central unit was disaggregated to the different orientations using the air volume that was distributed to the thermal zones as weighting factor.

The simulations were run for several European climates of which we will only show results for Berlin and Madrid as examples for a moderate and a hot climate. Whenever a glare condition occurred, an interior shade was lowered and stayed there for the remainder of the day. Based on the algorithm for glare control, east orientations were more affected by glare control than south or west orientations, because the interior shade was lowered earlier in the day. Fig. 7 and 8 show the results for a west oriented façade, which is the least affected by the assumed manual glare control. The trends are similar for both of the climates, the moderate Berlin climate and the hot Madrid climate.

4.1 Energy savings with exterior shades (no daylighting control)

Fig. 7a and 8a show EUI for the base glazing and the five exterior shades when constant electric lighting is assumed and no glare control is applied. The exterior shades significantly reduce EUI due to the reduced cooling load in summer. The effect is more pronounced in Madrid where cooling dominates energy use while in Berlin with its cold winters, the reduced solar gain for heating in winter counteracts the benefits in summer. With the best exterior shades (shd 6, 7a, 8) EUI can be reduced by approximately 60 kWh/m^{2}a in Berlin and by up to 120 kWh/m^{2}a in Madrid for a window-to-wall ratio of 60 %.

4.2 Energy savings with daylighting controls (no consideration of glare)

Fig. 7b and 8b show EUI for the same five exterior shades and the base glazing when there are daylighting controls assumed in the simulation model. The target illuminance was set to 500 lux and a continuous and linear dimming for the electric lighting (7.5 W/m^2) was modeled. The energy savings achieved with daylighting controls can be quantified by comparing Fig. 7a and 8a to Fig. 7b and 8b respectively. While without daylighting controls, EUI increases constantly with larger WWRs, with daylighting controls moderate WWRs between 30 and 45 % perform best. At a WWR of 60 %, the EUI is comparable with moderately-sized windows and remains below the fully opaque reference case except for the base glazing and shd 1.

4.3 Impact of glare control on EUI when using daylighting controls

Fig. 7c and 8c show simulation results for the building model with daylighting controls, and with additional glare control applied (described in Section 2.5 and based on the results shown in section 3). The comparison between Fig. 7b and 7c (Fig. 8b and 8c respectively) now shows the impact of glare control on EUI. Only the system with base glazing benefits from glare control as the interior shade reduces solar load to some extent, which results in 6 kWh/m^{2}a of savings for Berlin and 30 kWh/m^{2}a of savings for Madrid (WWR of 60 %) compared to the case without glare control through interior shades. These savings are small compared to the savings that one can achieve with exterior shades due to their advantage of blocking solar radiation outside the glazing.

Shd 1 and shd 2 experience a significant loss in performance when glare control is applied. Under the assumptions of daylighting control and manual glare control, there is no benefit of a horizontal slat shading system like shd 1. EUI for shd 2 increases by a maximum of 17 kWh/m^{2}a for Berlin and for Madrid (WWR of 60 %). EUI for shd 7, and 8 increases by a maximum of 9 kWh/m^{2}a; EUI for shd 6 does not increase.

5. Conclusion

We presented an approach how to integrate the occurrence of discomfort glare into building energy simulation. Therefore we linked the operation of an interior shade to the occurrence of a glare condition, which we defined as DGP ≥ 0.38 or DGI ≥ 24 for any of nine viewpoints in an open space office. DGP and DGI were often close in their evaluation, but for some situations we got significantly different results for DGP and DGI. The glare control algorithm combined both metrics and used numerical values for which glare is considered perceptible, but not necessarily intolerable. Different thresholds, different viewpoints or other metrics may lead to higher or lower numbers of predicted glare hours.

Building simulations were run for a prototypical office building and the transparent building envelope was varied. The reference case was run with a state of the art glazing system with a spectrally selective coating. For variations of the reference case we added five different exterior shades to the base glazing. The performance of the exterior shades in terms of discomfort glare varied widely: some were not showing discomfort glare at all while others showed a glare condition at 74 % of the office time.

We assumed daylighting controls in some of the simulation runs. When glare control was applied, daylight availability was reduced and for systems with frequent glare occurrence the calculated energy use was significantly greater than without glare control. The study showed the necessity to consider yet neglected influences such as discomfort glare and integrate subsequent occupant behavior in building energy simulation in order to close the gap between predicted EUI and energy use numbers in real buildings.

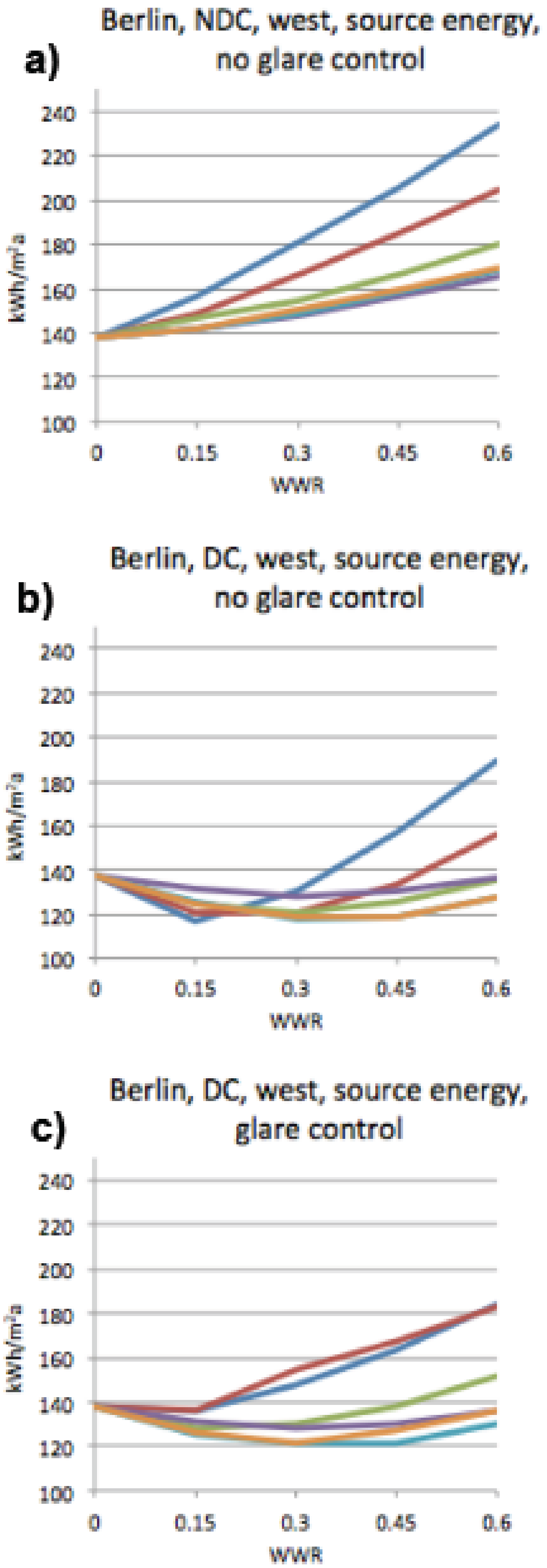

Figure 7 a-c: Energy use with and without glare control in the simulation model for Berlin

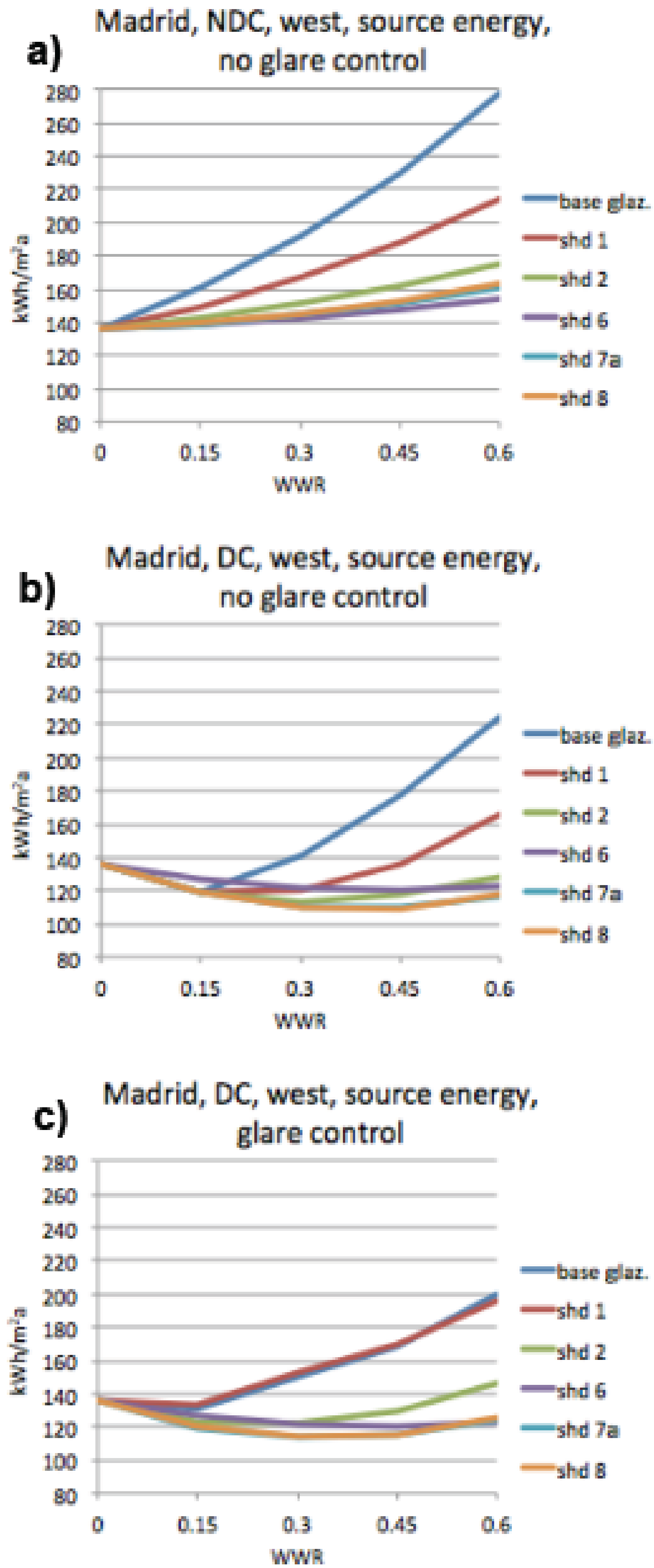

Figure 8 a-c: Energy use with and without glare control in the simulation model for Madrid

Nomenclature

L_S luminance of the glare source (cd/m^2)
ω_s solid angle of the glare source (sr)
$\omega_{pos,s}$ the solid angle of the glare source modified for its position in the field of view (sr)
P weight factor based on position in a viewing hemisphere, the position index
E_v total vertical eye illuminance (lux)
L_b background luminance determined by taking the average luminance of areas not identified as glare sources (cd/m^2)

References

[1] Hoffmann S, Lee ES. Potential Energy Savings with Exterior Shades in Large Offce Buildings and the Impact of Discomfort Glare. Conference Proceedings BEST 4, *Building Enclosure Science and Technology*, April 13 – 15, 2015, Kansas City
Available at: http://www.brikbase.org/content/potential-energy-savings-exterior-shades-large-offce-buildings-and-impace-discomfort-glare (accessed July 31, 2015)

[2] Hoffmann S, Lee ES, McNeil A, Fernandes L, Vidanovic D, Thanachareonkit A. The impact of daylighting and discomfort glare control on the potential energy savings of exterior coplanar shading. Submitted to *Energy and Buildings* on June 30, 2015. (Ref. No.: ENB-D-15-01149)

[3] Radiance GenBSDF http://radsite.lbl.gov/radiance/man_html/genBSDF.1.html (accessed July 31, 2015)

[4] Mitchell R, Köhler C, Klems J, Rubin M, Arasteh D, Huizenga C, Yu T, Curcija D. (editors) Window 6.2/ Therm 6.2 Research Version User Manual, Berkeley, CA, 2008. LBNL-941. Available at: http://windows.lbl.gov/software/window/window.html (accessed July 31, 2015)

[5] International Glazing Database http://www.nfrc.org/optical.aspx (accessed July 31, 2015)

[6] EnergyPlus InputOutputReference.pdf, Release V8.1.08. Available at: http://apps1.eere.energy.gov/buildings/energyplus/pdfs/inputoutputreference.pdf (accessed July 31, 2015)

[7] http://smartlouvre.com/ (accessed July 31, 2015)

[8] http://www.clauss-markisen.de/index.php?id=57 (accessed July 31, 2015)

[9] https://www.warema.de/PRIVATKUNDEN/PRODUKTE/Raffstoren/Abdunkelungs_Raffstoren.php (accessed July 31, 2015)

[10] Saxena M, Ward G, Perry T, Heschong L, Higa R. Dynamic Radiance – Predicting annual daylighting with variable fenestration optics using BSDFs. Proceedings of SimBuild 2010. 4th National Conference of IBPSA-USA. 2010 August 11-13. New York.

[11] Ward G, Mistrick R, Lee ES, McNeil A, Jonsson J. Simulating the Daylight Performance of Complex Fenestration Systems Using Bidirectional Scattering Distribution Functions within Radiance. Leukos 2011;7: 241-61.

[12] McNeil A, Lee ES. A validation of the Radiance three-phase simulation method for modelling annual daylight performance of optically complex fenestration systems. *Journal of Building Performance Simulation* 2012:1-14. doi:10.1080/19401493.2012.671852

[13] Wienold, J.. Evalglare: a new RADIANCE- based tool to evaluate glare in office spaces, 3rd International Radiance Workshop, Fribourg, CH, 2004.

[14] Wienold J, Christoffersen J. Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. *Energy and Buildings* 2006; 38: 743-757

[15] Jakubiec, JA, Reinhart CF. The 'adaptive zone' - A concept for assessing discomfort glare throughout daylit spaces. *Lighting Research and Technology* 2012; 44: 149-170.