Accepted for publication in *Building and Environment* (August 2010)

The Daylighting Dashboard - A Simulation-Based Design Analysis for Daylit Spaces

Christoph F. Reinhart[1] and Jan Wienold*

1 Harvard University, Graduate School of Design, 48 Quincy Street,
Cambridge MA 02138, USA
2 Fraunhofer Institute for Solar Energy Systems, Heidenhofstraße 2, 79110
Freiburg, Germany

Abstract

This paper presents a vision of how state-of-the-art computer-based analysis techniques can be effectively used during the design of daylit spaces. Following a review of recent advances in dynamic daylight computation capabilities, climate-based daylighting metrics, occupant behavior and glare analysis, a fully integrated design analysis method is introduced that simultaneously considers annual daylight availability, visual comfort and energy use: Annual daylight glare probability profiles are combined with an occupant behavior model in order to determine annual shading profiles and visual comfort conditions throughout a space. The shading profiles are then used to calculate daylight autonomy plots, energy loads, operational energy costs and green house gas emissions. The paper then shows how simulation results for a sidelit space can be visually presented to simulation non-experts using the concept of a daylighting dashboard. The paper ends with a discussion of how the daylighting dashboard could be practically implemented using technologies that are available today.

Keywords: Daylight Simulations, Radiance, Daysim, EnergyPlus, Daylighting Metrics, Glare, Daylight Autonomy

Introduction

The last decade has seen multiple advances of how to numerically analyze the overall performance of daylit spaces. These advances include a trend away from static and towards dynamic, climate-based daylight

---

[1] Corresponding Author: reinhart@gsd.harvard.edu

simulations (Reinhart, Mardaljevic et al. 2006; Mardaljevic, Heschong et al. 2009), more refined glare prediction and simulation methods (Wienold and Christoffersen 2006; Wienold 2007; Wienold 2009), occupancy behavior models that mimic occupant use of shading and lighting controls (Reinhart 2004; Haldi and Robinson 2009) and new evaluation methods to model the thermal and optical properties of complex fenestration systems such as light redirecting devices (ISO 2003; Kuhn 2006; Frontini, Kuhn et al. 2009)[2].

These innovations stand in harsh contrast to current daylighting design practice that still favors the use of rules of thumb during schematic design and largely relies on the daylight factor and illuminance distributions under clear sky conditions during solstice and equinox days (Galasiu and Reinhart 2007). One is left wondering why the design community at large is not picking up the above mentioned advanced design analysis schemes? Several barriers towards the adoption of these technologies come to mind:

1. <u>No single simulation environment:</u> Part of the problem may be that different technical advances have been realized in different simulation environments and without appropriate graphical user interfaces which makes them difficult and time-consuming to learn and whose use is therefore hard to justify for design teams.
2. <u>Simulation time:</u> Another practical concern is that some of the advanced daylight simulation techniques – especially those that rely on the Radiance raytracer (Ward and Rubinstein 1988) – tend to require prohibitively long computation times.
3. <u>Too complicated simulation process:</u> A recent study on modeling errors made by simulation novices of sixty-nine models of the same sidelit space found that the beginners' models had so many shortcomings that their relevance for the design process was questionable altogether (Ibarra and Reinhart 2009). If non-experts cannot even model the mean daylight factor in a standard sidelit space, what are the odds that they are going to get a fully integrated daylight/glare/thermal simulation right?
4. <u>Outdated rating schemes:</u> A missing driver for change is that building standards and rating schemes have generally remained rather static as far as daylight metrics are concerned, i.e. there is no immediate pressure for practitioners to move towards more advanced daylighting analysis.
5. <u>No clear understanding of simulation outcomes:</u> An additional barrier is that casual software users - even if they happen to get the simulations right – oftentimes lack the expertise to interpret the simulation results as well as the know-how to fix the design problems raised by the simulation.

Barriers 1 to 3 are important but mainly technical in nature. The authors

---

[2] A detailed review of these techniques is provided under Reinhart, C. F. (2010). Simulation-based Daylight Performance Predictions. <u>Building Performance Simulation for Design and Operation</u>. J. Hensen and R. Lamberts, Taylor and Francis.

believe that *if* senior design decision makers and code authorities can be convinced that computer-based daylighting analysis can facilitate the design of better daylit buildings (barriers 4 and 5), *then* the financial incentives will be made available for software developers, educators and others to overcome these technical barriers.

At the time of writing, barrier 4 was actually not fully valid any more as several rating systems either had already or were in the process of introducing daylighting compliance paths that are derived from climate-based illuminance metrics. Examples are the Collaborative for High Performance Schools (CHPS 2010), the International Green Construction Code (ICC 2010) and LEED for Schools (USGBC 2009). While the authors clearly feel that these changes are a step in the right direction, we also hope to highlight with this paper that there still is a large discrepancy between the type of daylighting analysis that these new compliance paths are about to require as opposed to what can already be done. This is not surprising since daylight autonomy calculations were already introduced in 2001 and research has steadily advanced since then (Reinhart and Walkenhorst 2001).

This paper hence aims to provide a vision of where computer-based daylight performance analysis should be going. Initially, several promising advances in building performance evaluation of daylit spaces are being reviewed and combined into a fully integrated building performance simulation that considers annual daylight availability, glare and thermal loads for a daylit space. An example application is being presented for a simple sidelit office. The ensuing discussion reflects on how such a comprehensive but complicated design analysis can be presented to owners and designers without expert simulation knowledge using a ‘daylighting dashboard’. Finally, the practicality of using the method in a BIM type simulation environment for complicated, large buildings that consist of hundreds of spaces is being addressed.

2. Simulation-based Daylighting Analysis

In this section a simulation-based daylighting analysis for buildings is developed. This task leads back to the age-old question of what constitutes good daylighting? In a 2007 survey of 177 design practitioners the participating ‘designers’ leaned towards the definition of daylighting being “the interplay of natural light and building form to provide a visually stimulating, healthful and productive interior environment” whereas the ‘engineers’ tended towards the “the use of fenestration systems and responsive electric lighting controls to reduce overall building energy requirements (heating, cooling, lighting)” (Galasiu and Reinhart 2007). The response pattern revealed a need within design teams to carefully define the meaning of the term ‘daylighting’ at the beginning of a project as well a potential for conflict since esthetics, energy efficiency and occupant comfort cannot necessarily be optimized in parallel. It is the authors’ subjective conviction that a space that is either *not* energy efficient or *un*comfortable cannot be called ‘successfully daylit’. We therefore propose a hybrid definition of daylighting i.e. *a space that is primarily lit with natural light and that combines high occupant satisfaction with the visual and thermal environment with low overall energy use for lighting, heating and cooling*. Daylighting design hence becomes a tradeoff between optimizing the annual daylight availability within a space while making sure that the space is energy efficient and exhibits high occupant satisfaction.

The reader may wonder whether energy-efficiency and occupant satisfaction with the lighting do not suffice as requirements for good daylighting? The authors believe that daylight availability is an essential requirement for daylighting due to growing evidence that the *existence* of personal environmental controls (movable shades, light switches and operable widows) may already positively influence occupants’ indoor environmental satisfaction which does not necessarily mean that the environment is actually objectively better. Along the same lines, a recent survey of 183 school teachers in New York City found that while 70% of the teachers rated the overall lighting quality in the classrooms ‘good’ to ‘excellent’ a third of them kept their opaque roller shades permanently lowered and another 21% adjusted them ‘once or twice a month’ (Sze 2009). I.e. daylight was mostly eliminated from those classrooms even though most of the surveyed classrooms had 2.1 to 2.4m high window head heights and had thus been originally designed with daylighting in mind. With many of the shades lowered, building occupants were typically not reporting any visual discomfort related to glare. Still, the authors would not call those classrooms ‘well daylit’. The example reiterates the fact that occupants’ visual comfort conditions and the resulting use of light switches and shading devices are inseparably linked to the daylit performance of a space and should not be ignored even during the earlier design stages.

2.1 Simulations

Now that three performance categories for daylight - daylight availability, visual comfort and thermal loads - have been established, the reminder of this section reviews a series of metrics that can be used to evaluate these categories. To make the discussion more tenable for the reader, the metrics are being applied to the simple sidelit space from Figure 1. The space is located in Boston, MA, (42.3°N, 71.1°W) and has an unshaded, South-facing façade with a spectrally selective double glazing with a direct normal visual transmittance of 72% and a solar heat gain coefficient of 62%. The ceiling, walls, and floor have purely diffuse reflectances of 80%, 50% and 30%, respectively. The space is used as an office (target work plane illuminance of 500 lux) and occupied on weekdays from 8 AM to 5 PM. The lighting power density and equipment load in the office are 8 Wm^{-2} and 9 Wm^{-2}, respectively.

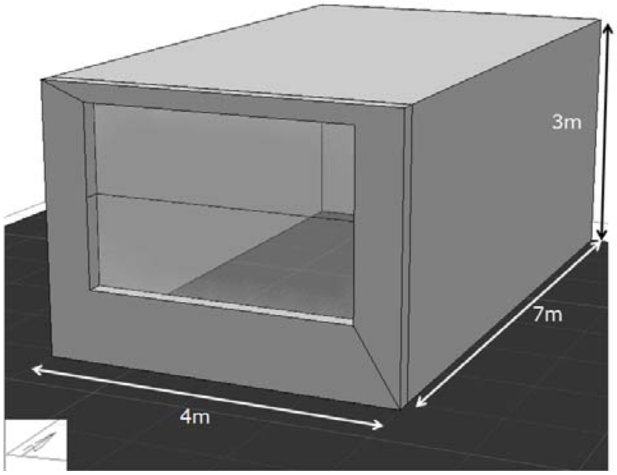


Figure 1: Example sidelit space.

The space was simulated with and without manually controlled external venetian blinds. The blind slats were assumed to be 80mm wide, to extend across the whole window width and to have a diffuse reflectance of 80%. All daylight simulations were carried out using the validated Radiance-based Daysim program version 3.0 (DDS format) (Reinhart last accessed Mar 2010). Radiance is a backward raytracer developed by Ward (Ward and Shakespeare 1998). Daysim uses Radiance to calculate annual illuminance or luminance profiles based on local climate data and a daylight coefficient approach (Bourgeois, Reinhart et al. 2008). The Evalglare program extracts daylight glare probabilities from Radiance images and/or high dynamic range photographs (Wienold last accessed in March 2010). All daylighting models were built and the results were visualized in Autodesk Ecotect (Marsh last accessed March 2010). Table 1 shows the Radiance simulation parameters that were used for all daylight simulations.

Table 1: Utilized Radiance simulation parameters.

ambient bounces	ambient division	ambient sampling	ambient accuracy	ambient resolution	direct threshold
5	1000	20	0.1	300	0

For the thermal simulations it was assumed that the space is bordered on five sides by similar spaces (see Figure 2). As a consequence, interior walls, floor and ceilings were modeled adiabatically. The exterior wall has a U value of 0.35 W/m^{2}K. The space is conditioned with a fan coil unit powered by natural gas for heating and electricity for cooling. Coefficients of performance are 0.83 and 1.67, respectively. Heating and cooling setpoints and setbacks are 21°C/14°C and 25°C/30°C, respectively. All thermal simulations were set up in DesignBuilder V2 (DesignBuilder 2010) and run using EnergyPlus version 5.0 (US-DOE 2010). Annual hourly schedules for occupancy, electric lighting and the status of the blinds were generated in Daysim and read as simulation input into EnergyPlus.

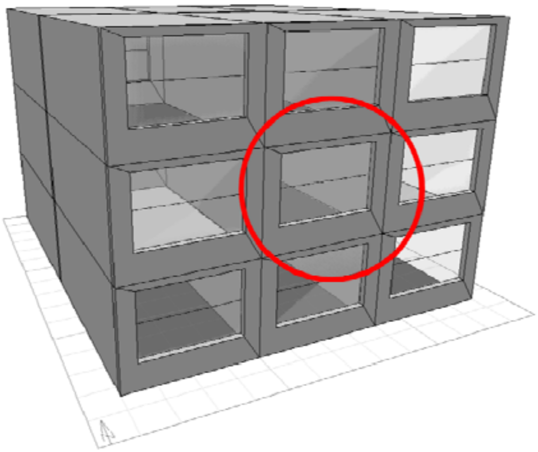


Figure 2: For the thermal simulation the space was assumed to be bordered by thermally similar spaces.

Figure 3 summarizes the overall simulation approach. It is worthwhile to stress that the space was modeled twice for this study, once in Autodesk Ecotect for the daylight simulations and once in DesignBuilder. This step could have potentially been avoided since the latest version of DesignBuilder exports Radiance files and since Autodesk Ecotect has some export functionality to EnergyPlus. But, this approach was chosen since the model geometry was extremely simple and since it allowed the authors to sidestep any software interoperability issues. Obviously a more integrated workflow would be required for a more complex building (see discussion section).

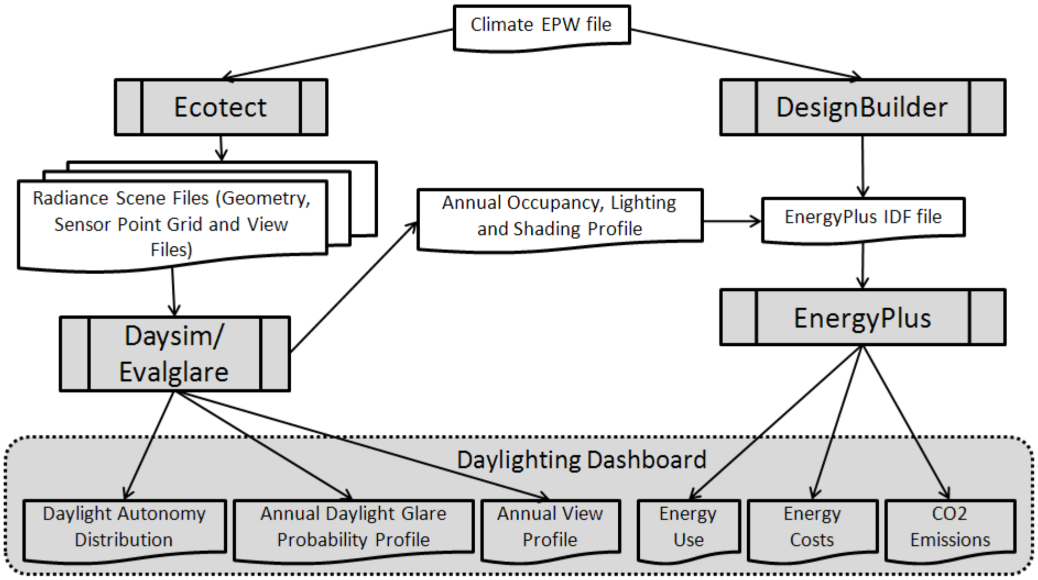


Figure 3: Overall simulation approach used in this study.

2.2 Daylight Availability

The annual amount of daylight in a space can nowadays be quantified via so called dynamic or *climate-based metrics*. As the name suggests, these metrics are derived from annual illuminance profiles, i.e. hourly or even sub-hourly time series of interior illuminances or luminances due to daylight that are generated using a local climate file (Mardaljevic 2000; Reinhart and Walkenhorst 2001). In order to become usable for design, this massive amount of data has to be converted into an intuitive metric. The first step in this conversion process is to decide on which times of the year the analysis should be based. A common choice is to concentrate on the times when the investigated space will be occupied since daylight 'needs witnesses' to have an effect (Reinhart, Mardaljevic et al. 2006). This approach goes hand in hand with the one taken by energy simulation programs that also assume typical usage patterns.

The next step of the analysis is to decide what daylighting levels to consider 'adequate'. Here the two currently most commonly used approaches are daylight autonomy (DA) and useful daylight illuminance (UDI). Figure 4 shows DA and UDI distributions for the space from Figure 1. DA is defined as 'the percentage of the occupied hours of the year when a minimum illuminance threshold is met by daylit alone' (Reinhart C F & Walkenhorst O, 2001). The metric uses the target illuminance for a space according to IESNA requirements (IESNA 2000), 500 lux in the case of Figure 4. In order to divide the space into a 'daylit' and a 'partially daylit' area the grayscale for the daylight autonomy figure is set to saturate to white for DA values above 48% which corresponds to *half of the DA value for an unshaded outside point with the same occupancy schedule and illuminance threshold requirement for this particular climate.* I.e. an interior area is interpreted to be daylit if it receives at least half the time sufficient daylit compared to an outside point. The grayscale area in the back of the space indicates varying DA values from 0% to 48%. The DA figure suggests that the daylit area extends across the two thirds of the room adjacent to the window which corresponds to about 1.5 times the window head height (Reinhart 2005).

Figure 4 also shows the three related UDI distributions for the space. UDI uses lower and upper thresholds of 100 lux and 2000 lux and accordingly divides the year into three bins (Nabil and Mardaljevic 2005; Nabil and Mardaljevic 2006). The upper bin ($UDI_{>2000lux}$) is meant to represent times when an oversupply of daylight might lead to visual and/or thermal discomfort, the lower bin ($UDI_{<100lux}$) represents times when there is 'too little' daylight and the intermediate bin ($UDI_{100\text{-}2000lux}$) represents 'useful' daylight. The $UDI_{100\text{-}2000lux}$ metric suggests that there is useful daylight in the *back* two thirds of the space whereas the $UDI_{>2000lux}$ metric flags an oversupply of daylight near the façade. These warnings are plausible given the size of the South-facing glazing of the investigated space (window-to-wall ratio = 50%).

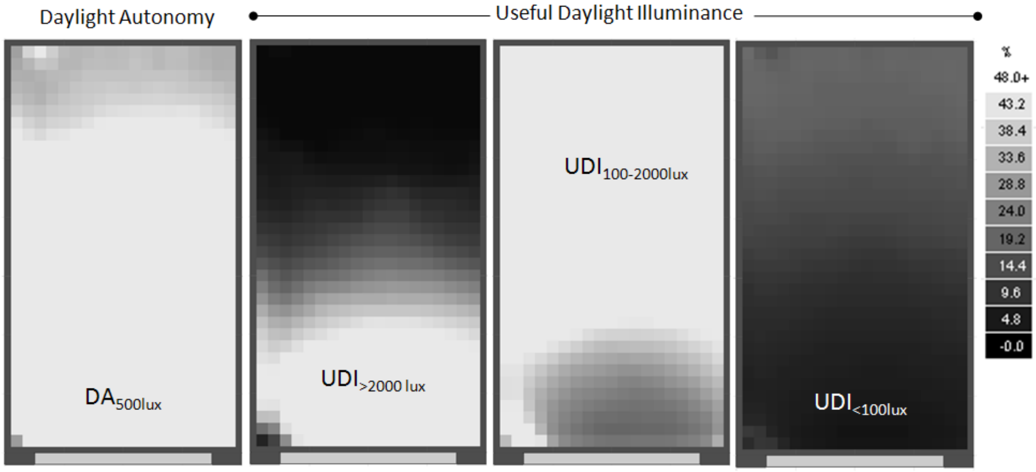


Figure 4: Plan view of the Daylight Autonomy and Useful Daylight Illuminance distributions in the sidelit office from Figure 1.

Figure 5 proposes a new metric termed 'daylight availability' that is meant to amalgamate DA and UDI information into a single figure. The white and grayscale areas correspond to the regular daylight autonomy distribution. The diagram further distinguishes an 'over lit' area (red) near the window. The 'over lit' area presents a warning that is invoked if an oversupply of daylight is assumed for at least 5% of the working year. The 5% criterion was selected as an analogue method to thermal assessments according to British Standard BS EN 15251(BSI 2007). The standard defines threshold levels for several thermal comfort categories which may be exceeded 3-5% percent of the occupied times of the year. In Figure 4 an oversupply is assumed if the illuminance level is above ten times the target illuminance. This criteria corresponds to the DA_{max} metric proposed by Rogers (Rogers 2006). Other threshold levels may e.g. be defined based on the daylight glare probability metric (see below) (Wienold 2009). Same as the $UDI_{>2000lux}$, the daylight availability metric predicts an oversupply of daylight in the third of the space adjacent to the façade.

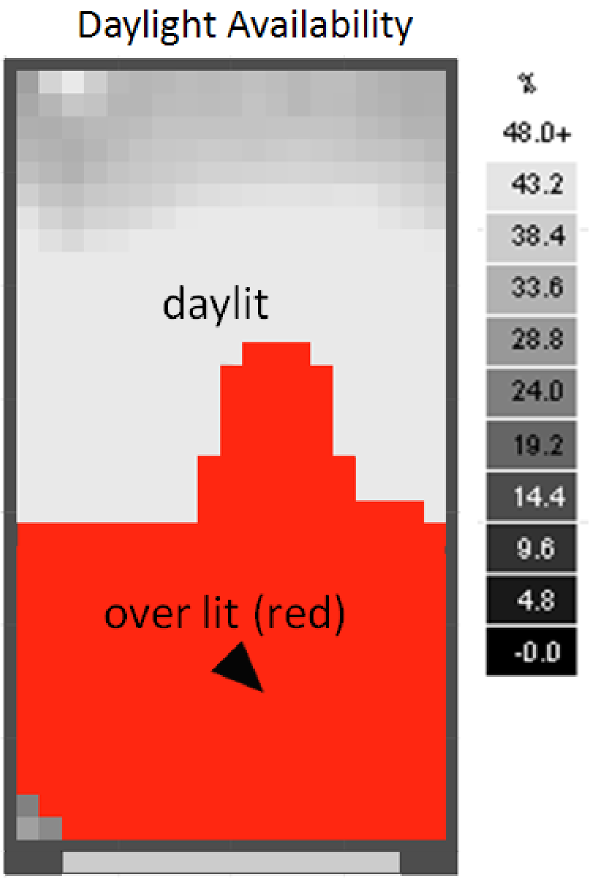


Figure 5: Plan view of the Daylight Availability in the sidelit office from Figure 1.

Figure 6 shows a way to further investigate the area of daylight oversupply from Figure 5 using a *temporal map*. A temporal map is a falsecolor map with the day of the year mapped along the X axis and the time of day along the Y axis (Mardaljevic 2004; Kleindienst, Bodart et al. 2008). Figure 6 shows a temporal map of the horizontal illuminance at the point marked with the black triangle in the daylight availability diagram in Figure 5. The temporal map shows that the horizontal illuminance near the center of the triangle experiences levels above 5000 lux from about 10 AM to 3 PM from September to April, suggesting that the use of a shading device is required during those times. Since the oversupply happens all year around, the most meaningful design advice is to either reduce the window size or to introduce a movable shading device. As the name suggests, a temporal map presents performance over time referring to a single or several points in a space. In contrast, the earlier discussed metrics concentrate on the spatial patterns of daylight but summarize over the whole year. Temporal and spatial maps should ideally be used in combination, i.e. Figures 5 suggests that there is too much daylight near the façade and Figure 5 shows that the oversupply happens during the winter and shoulder seasons.

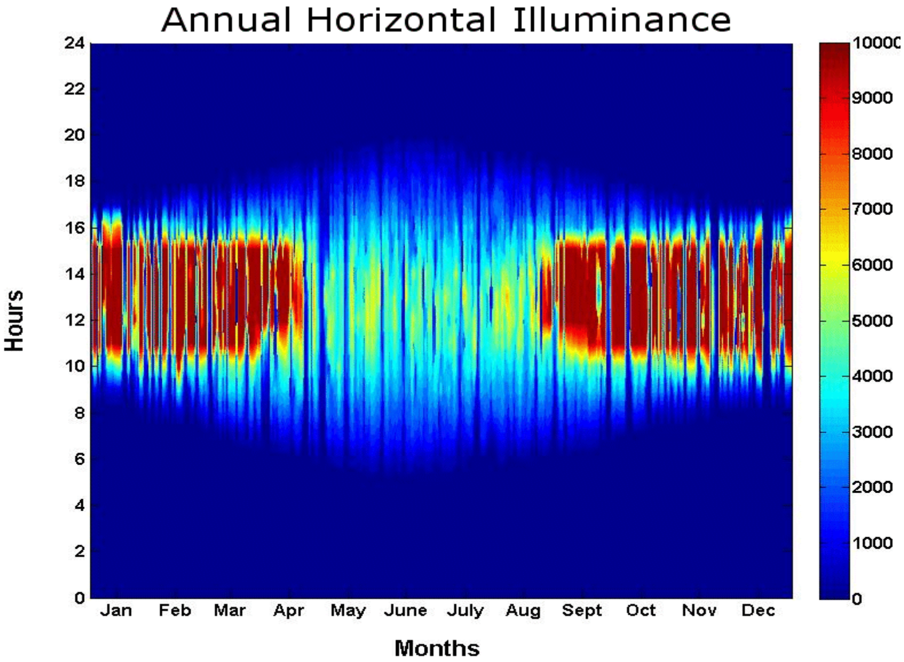


Figure 6: Temporal map of the point marked with a triangle in Figure 5.

2.3 Visual Comfort

While the previous section presented attempts to summarize the annual daylight availability within a space, this section is moving towards ways to further predict visual comfort. Two metrics for visual comfort are being presented, absence of discomfort glare and a view to the outside.

2.3.1 Discomfort Glare

Glare is a subjective human sensation that describes 'light within the field of vision that is brighter than the brightness to which the eyes are adapted' (HarperCollins 2002). Glare is typically divided into *disability glare*, which is the inability of a person to see certain objects in a scene due to glare, and *discomfort glare*, the premature tiring of the eyes due to glare. While disability glare in daylit interiors is relatively easy to identify, discomfort glare is a more subtle, subjective phenomena that is closely linked to a person's overall indoor environmental satisfaction. Predicting the appearance of discomfort glare in daylit spaces has been studied for many years. There is a widely shared notion that horizontal work plane illuminance - while easy to measure - is a poor predictor of discomfort glare as the amount of light falling on a working area has little in common with a person's visual experience of a space. Instead, glare analysis should be based on the luminance distribution in the field of view of an observer. A *glare index* is a numerical evaluation of high dynamic range images using a mathematical formula that has been derived from human subject studies. Example indices include the unified glare rating (UGR) and the daylight glare index (DGI). All of these equations were derived from experiments with artificial glare sources – none of them under real daylight conditions (Wienold and Christoffersen 2006). The reason for this is that until recently it has been next to impossible to collect high dynamic range images of daylit scenes under continuously changing lighting levels. Daylight glare probability (DGP) is a recently proposed discomfort glare index that was derived by Wienold and Christoffersen from laboratory studies in daylit spaces using seventy-two test subjects in Denmark and Germany. In the experimental setup, two identical, side-by-side test rooms were used. In one of the rooms a CCD camera based luminance mapping technology was installed at the exact position and orientation as the head of the human subject in the other room (Wienold and Christoffersen 2006). DGP is defined by the following equation:

$$DGP = 5.87 \times 10^{-5} E_v + 9.18 \times 10^{-5} \log\left(1 + \sum_i \frac{L_{s,i}^2 \omega_{s,i}}{E_v^{1.87} P_i^2}\right) \qquad \text{(Equ 1)}$$

where E_v is the vertical eye illuminance; $L_{s,i}$ is the luminance of source 'i'; $\omega_{s,i}$ is the solid angle of source i and P is the position index, a weighing function that varies with the distance of a glare source form the field of vision. Figure 7 shows two visualizations and associated DGPs for the workplace and orientation marked by the triangle in the DA diagram in Figure 5 under a CIE clear and overcast sky on March 21st at 3PM. The associated DGPs for the overcast and clear skies are 22% and 41%, respectively. The values fall into subjective glare ratings of less than 'imperceptible' and 'disturbing' (Wienold 2009).

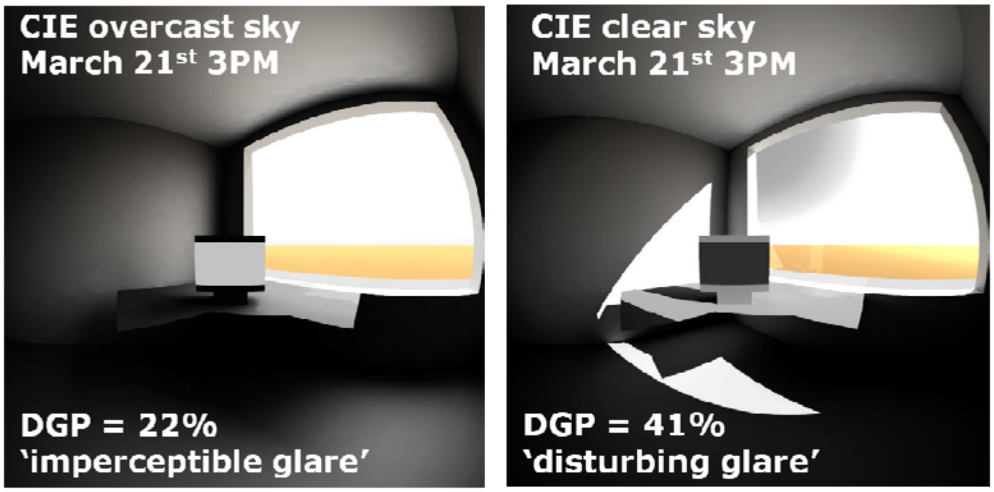


Figure 7: Radiance visualizations and associated DPGs for the workspace marked by the triangle in Figure 3 on March 21st at 3PM under a CIE clear (a) and overcast (b) sky.

In order to evaluate the overall appearance of discomfort glare at a workspace over the course of the year, it becomes necessary to repeat the analysis from Figure 7 for all hours of the year using site-specific climate data. Wienold proposed a simplified method that uses daylight coefficient based vertical eye illuminance and simplified images in order to calculate annual DPG profiles more efficiently than running one full scene visualization at each time step (Wienold 2009). As an example, Figure 8 shows the cumulative annual DGP distribution for the workspace from Figure 7 assuming working hours on weekdays from 8 AM to 5 PM using Wienold's *enhanced simplified DGP* method. In order to guide the eye, the figure shows the DGP ranges in which human subjects rated the glare within their field of view to be imperceptible, perceptible, disturbing and intolerable (Wienold 2009).

The figure reveals that the DGP value at the workplace is for 1015 working hours (39% of the occupied time) in the 'intolerable' glare range suggesting that the workplace has unacceptable visual comfort conditions. The analysis shows that annual DGP profiles present a powerful way of evaluating the appearance of discomfort glare in a space.

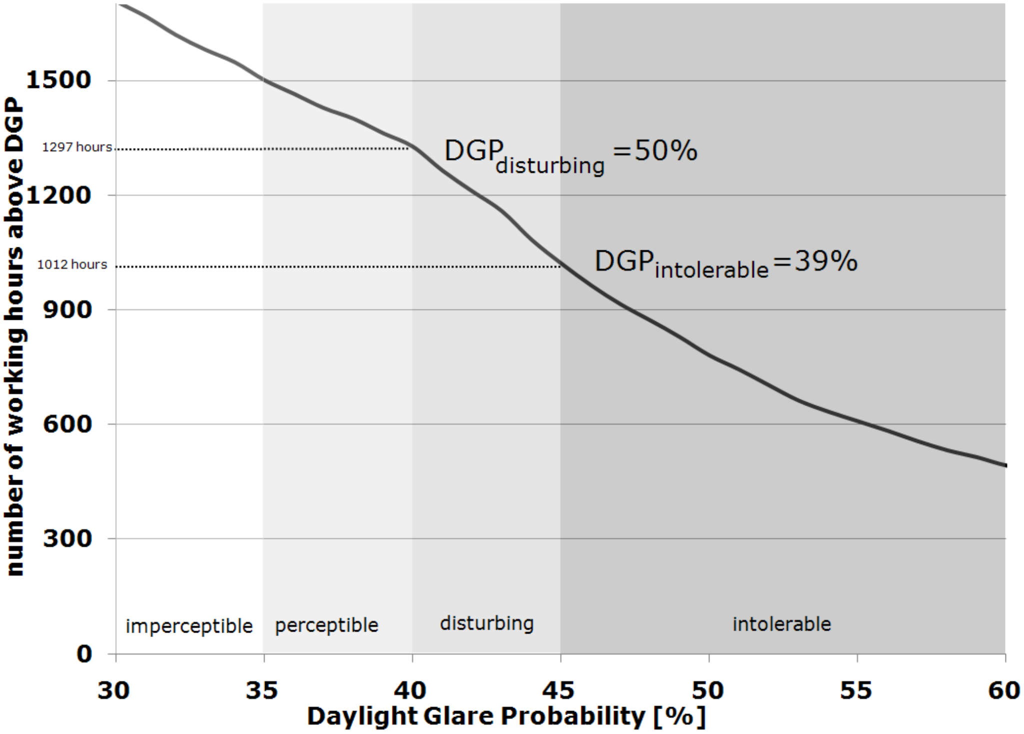


Figure 8: Annual cumulated DGP profile the workspace marked by the triangle in Figure 5.

2.3.2 Modeling Occupant Behavior

It has by now been established in multiple ways that the space from Figure 1 - if used as an office with the occupant sitting in vicinity to the window - would require the use of a glare protection device. If the use of a static shading device (or a smaller window) was desired, the modeller would simply have to repeat the previous analysis with the shading device added to the scene. But, in real life, a manually operated movable shading device such as a venetian blind would be a likely choice for such a space. In order to model the effect of such a system, multiple annual illuminance and DGP profiles have to be carried out for at least two representative blind positions such as fully opened and fully lowered with a slat angle that blocks direct sunlight under most sky conditions. Figure 9 shows the annual DGP profiles and daylight autonomy distributions on the center axis of the space for a variety of different blind usage patterns. The ‘no blinds’ and ‘passive user (blinds always lowered)’ scenarios show the magnitude of the simulation uncertainty introduced by the occupant. The ‘true’ occupant behavior is likely to lie somewhere in between these two extremes. In order to get a better estimate, an ‘occupant behavior model’ such as *Lightswitch 2002* can be used. The Lightswitch model was derived from field study data that monitored long term occupancy and use of light switches and shading devices in private and two-person offices (Reinhart C F, 2002). Lightswitch accordingly mimics how occupants interact with manually and automatically operated lighting controls and shading devices and uses occupancy, work plane illuminance and the appearance of direct sunlight at the workspace as input data. A key assumption of the model is that occupant behavior can be described through two archetypical behavior patterns called ’active’ and passive’ users. For the active user an expanded version of the original model further distinguishes between a user who closes the blinds for the day once direct sunlight above 50Wm^{-2} is incident on the work space (‘active blind use (avoid direct sunlight)’) and a user who closes the blinds for the day once the DGP at the workplace becomes ‘disturbing’(>40%) (Wienold 2007). Both active users raise their blinds once a day during arrival. A passive user keeps the blinds lowered all year.

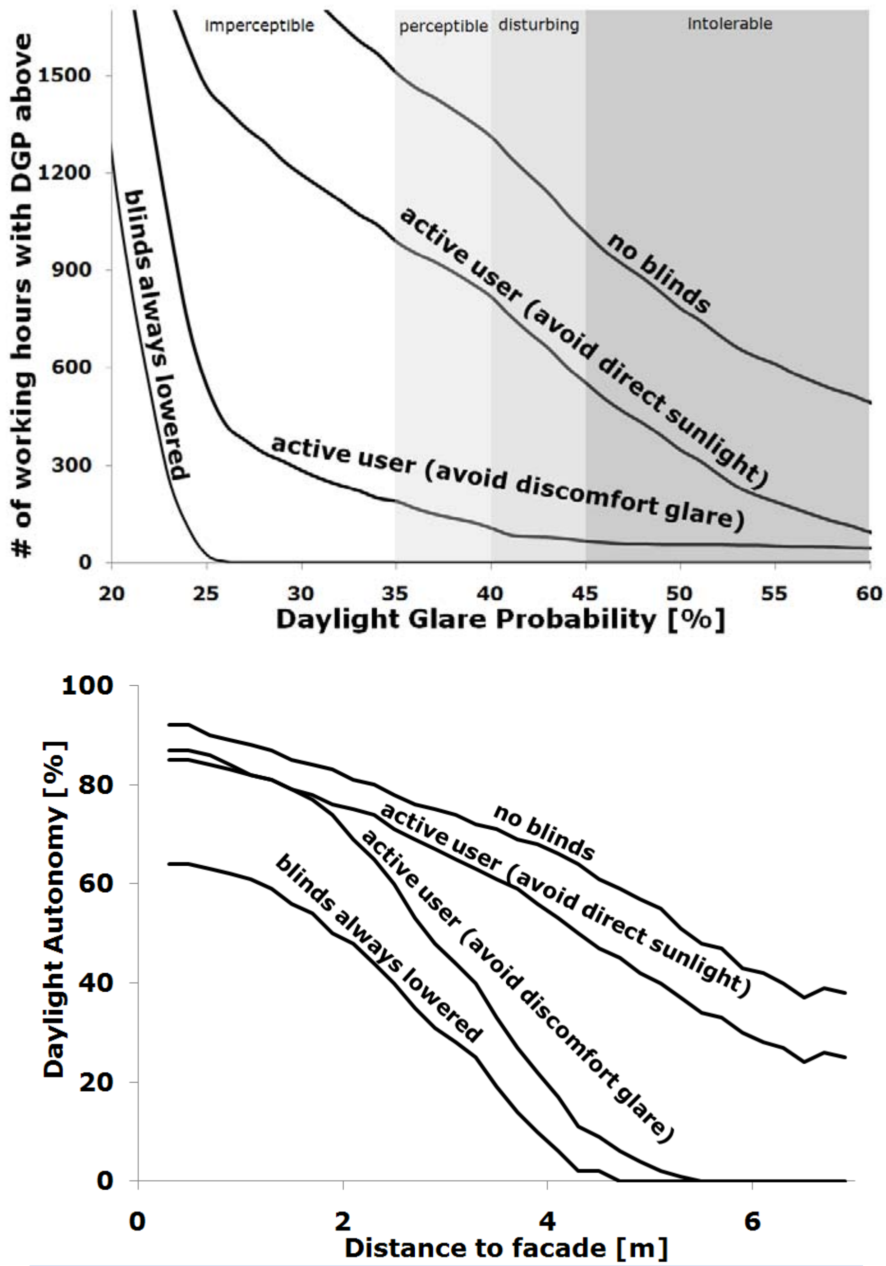


Figure 9: Annual DGP profiles (a) and DA distributions (b) for the space from Figure 1 assuming different blind control strategies.

Figure 9(a) shows that the presence of a venetian blind reduces the number of hours with ‘intolerable’ DGP to 553, 66 and no hours for the two active and the passive users, respectively, revealing that a venetian blind can alleviate visual discomfort in the space, if operated accordingly by the user. These DGP exceedances translate into occupancy rates of 21%, 3% and 0% of the year. Figure 9(b) reveals that the addition of venetian blinds reduces the daylit area to 2 to 4 m away from the façade for the different occupant behavior patterns.

It is worthwhile to note that modeling a manually operated shading device requires - as a additional simulation input parameter - an educated guess of where the occupant operating the device is usually located. This can lead to situations during which discomfort glare near a façade leads to the closing of venetian blinds which in turn results in an undersupply of daylight for another occupant further away from the façade. The resulting group dynamics between occupants are not well understood, yet. There is also little known about how occupants operate multiple sets of blinds in a space or how many occupants in a building a designer can expect to be either active or passive users. Occupant behavior models - such as Lightswitch - are further based on data collected from a very limited number of human subjects and buildings and hence need further validation through more field work. Despite of these shortcomings, the authors believe that not considering the use of blinds at all leads to misleading design interpretations: The reader might consider the UDI diagrams from Figure 4. There seems to be plenty of usable daylight in the *back* of the space paired with an oversupply of daylight *near* the façade. But, if used as an office, the space would likely be equipped with venetian blinds that provides good daylight *near* the façade but insufficient daylight in the *back* (Figure 9). The design conclusions are exactly opposite.

2.3.3 View

While there is a widely shared notion that one of the benefits of vertical windows is the provision of a view to the outside, there is less consensus of what actually constitutes a view (Farley and Veitch 2001). The LEED green building rating system defines view as a straight visual connection from an interior point to a point outside through a façade opening located within a certain height range within a façade (USGBC 2009). This criterion neglects several items that are known about view namely that a view is more than just a physical connection to the outside but must also carry ‘information of visual interest’ such as landscape or a busy street. Another aspect of a view through a window with a movable shading device is that the device might obstruct view at certain times of the year. Thus, in order to rate a view through a window several steps are required: First one has to determine whether a window actually does provide a view. This could translate into a yes/no criterion or be further refined into a quality of view rating. Let’s assume for our example space that it does have a ‘full’ view for the work place under consideration.

The next step is then to count the occupied hours of the year when the shading device is retracted. For the four blind control strategies from Figure 9 this translates into the annual view availabilities shown in Figure 10.

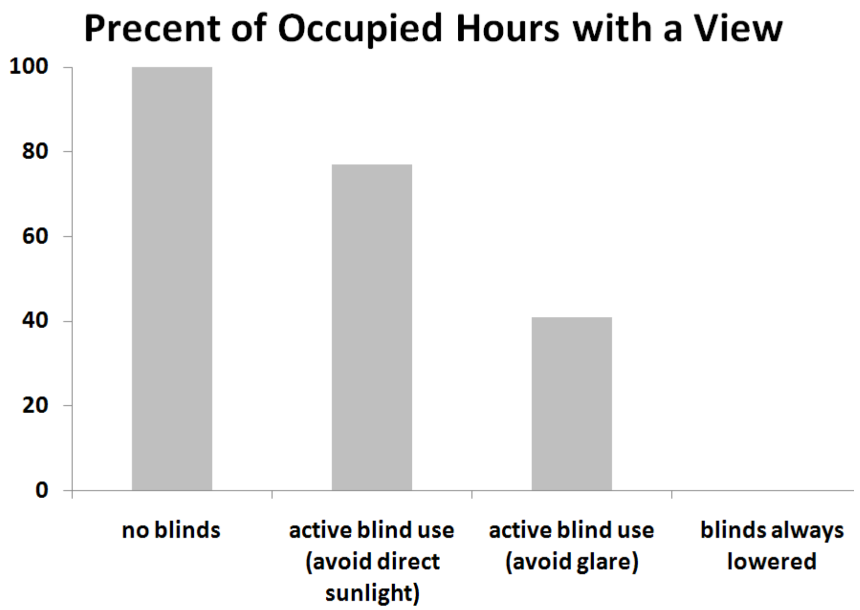


Figure 10: Percentage of the occupied time of the year when the occupants have a view (blinds are retracted).

The figure shows that for the two extreme cases of *no blinds* and *blinds always lowered* the view (obviously) changes from 100% to 0%. More interestingly, the two active blind uses have significantly different view percentages varying from 41% to 77%.

2.4 Energy Use, Costs and Carbon Emissions

In order to evaluate energy-related implications of a daylighting concept, the simulation assumptions from the daylighting analysis need to be synchronized with the thermal analysis. For the present study this synchronization was realized though Daysim writing out hourly schedules that include occupancy as well as the status of the electric lighting and blinds. This schedule file was then read into the EnergyPlus model of the space (Figure 3). The resulting annual energy uses for heating, lighting and cooling are shown in Figure 11. Note that there are two results for the *no blinds* case because, while the daylighting cannot be affected by the user in a space without a movable shading device, occupants may still control the electric lighting differently which in turn impacts the heating and cooling load in the space. Figure 11 shows that the presence of external venetian blinds lowers the electric lighting and cooling use in the building for both active and passive users but significantly increases the heating load. This result is in line with what one would expect as external venetian blinds are very effective at blocking solar gains from entering a building which is desirable in summer but less so in winter.

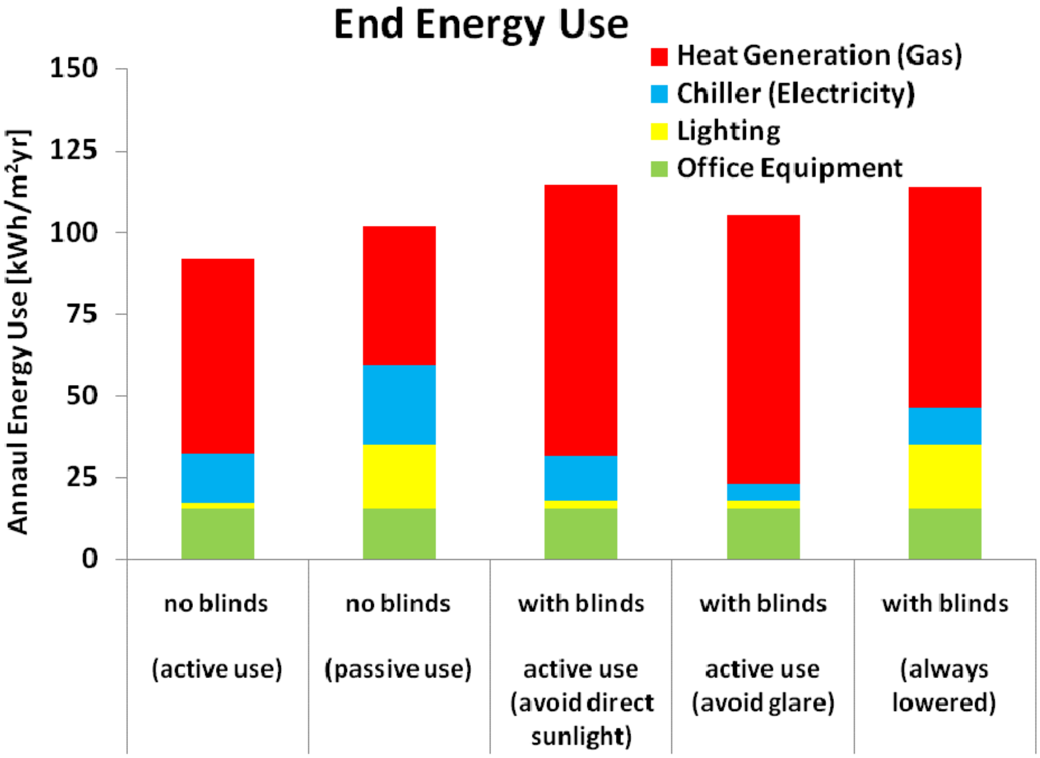


Figure 11: Annual energy use for heating, cooling and electricity in the space for different blind control strategies and occupant behavior patterns.

Figure 11 is somewhat misleading since electricity and gas use cannot be directly compared because both sources of energy have different costs and environmental impacts associated with them. Figure 12 therefore shows energy costs and equivalent carbon emissions for the office assuming electricity and natural gas prices of 14.4 and 3.5 cents/kWh as per the US Energy Information Administration for Boston (EIA 2010). The CO_2 equivalent emission factors for electricity and natural gas of 0.758 and 0.232 kgCO_2e/kWh were taken from ASHRAE 189.1 (ANSI/ASHRAE/USGBC/IES 2010).

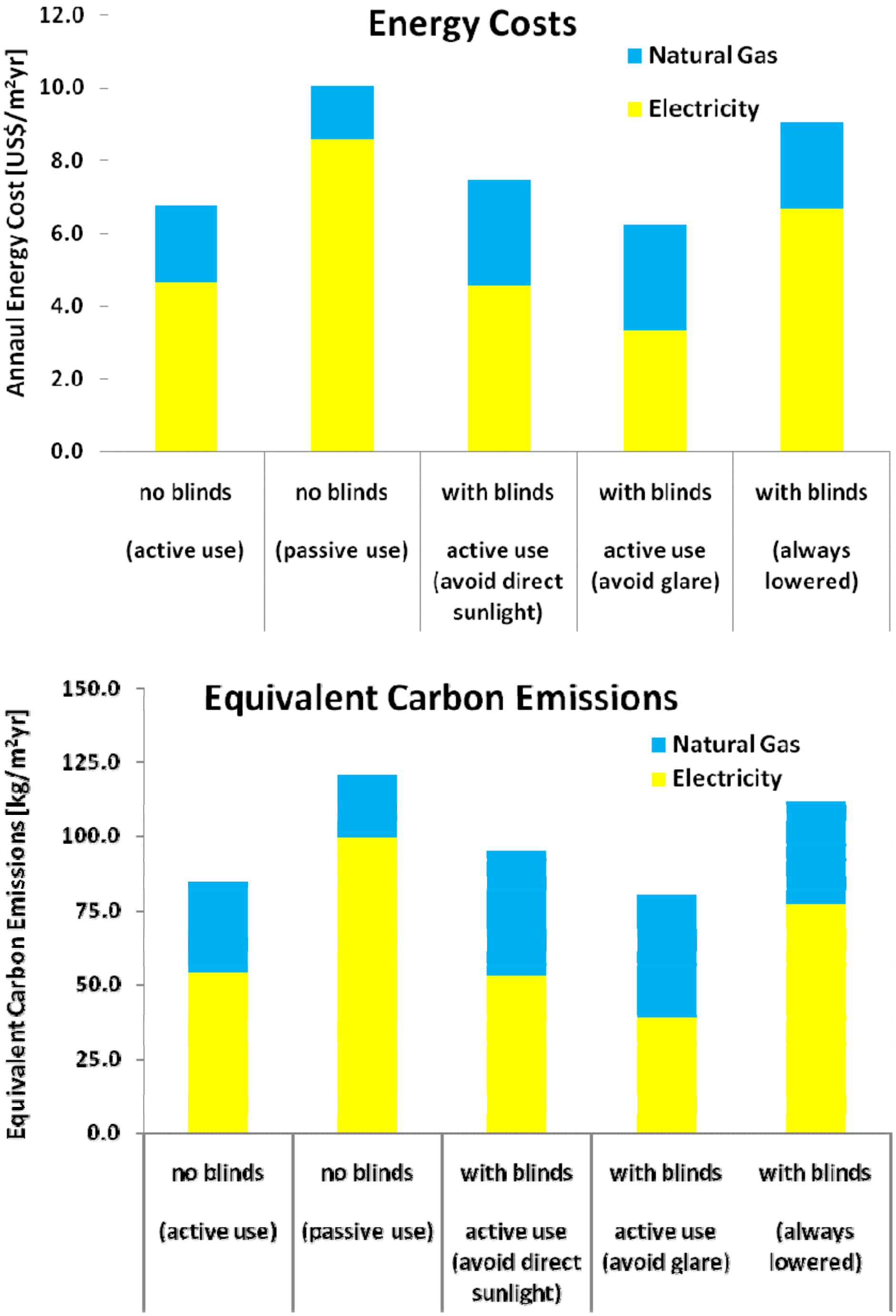


Figure 12: Annual operational energy costs and equivalent carbon emissions for the space for different blind control strategies and occupant behavior patterns.

Figure 12 shows that for a passive user the introduction of an external venetian blind lowers the energy costs and carbon emissions by 6% and 10%, respectively. For the active user the quantities stay about the same.

3. Daylighting Dashboard

The previous section covered a range of design analysis methods that one can apply to a simple sidelit space with and without external venetian blinds. While the information - as presented - might be useful for an energy consultant, it is probably too complicated to digest for other members of the design team in a short period of time. Also, once this type of comprehensive analysis is carried out for a whole building with potentially hundreds of work spaces and thermal zones, the information becomes next to impossible to synthesize in this format. This section therefore aims to recompile the simulation results from the previous section in a more intuitive, visual fashion. The recompilation specifically addresses two questions: How to deal with uncertainty introduced into a simulation by occupant behavior as well as how to deal with multiple spaces?

3.1 Occupant Behavior

While our understanding of occupant use of lighting and shading controls is increasing, we are still missing some basic information such as what the population density of our behavioral archetypes - active and passive users – is for different space types. This distribution probably varies with the cultural context of a building population as well as specific design choices within the building such as how accessible personal environmental controls are. In absence of this knowledge, critics of occupant behavior models might argue that they are not sufficiently reliable, yet, to base design decisions on them. The authors would counter this argument by referring to the previous section that clearly showed that variations in occupant behavior have too large of an impact on occupant comfort and energy use to be fully ignored. Instead, we are recommending to work with just two behavior profiles: An *active user* who exhibits a preference for daylight over electric lighting while avoiding glare and a *passive user* who keeps the blinds lowered and the electric lighting on all year. One can interpret the results for the two users by declaring that the active user operates a building according to its ‘design intentions’ whereas the passive user results give an indication of how robust a building design is towards occupants working against it. In bar charts and plot diagrams this interpretation can be visualized by showing the results for the active user as regular data and marking the results for the passive user with respect to the active user by an error bar. Using this approach, Figures 9 to 12 can be significantly simplified into a *Daylighting Dashboard* view that presents all six performance metrics for one or several spaces and/or design variants (Figure 13).

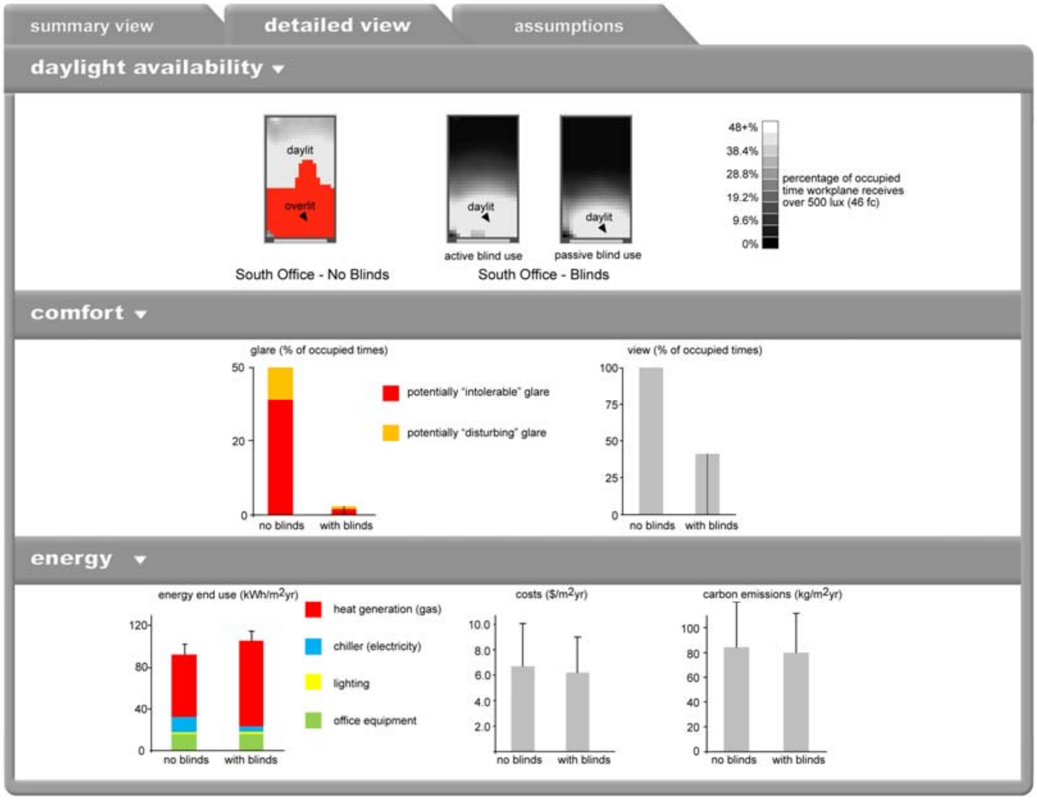
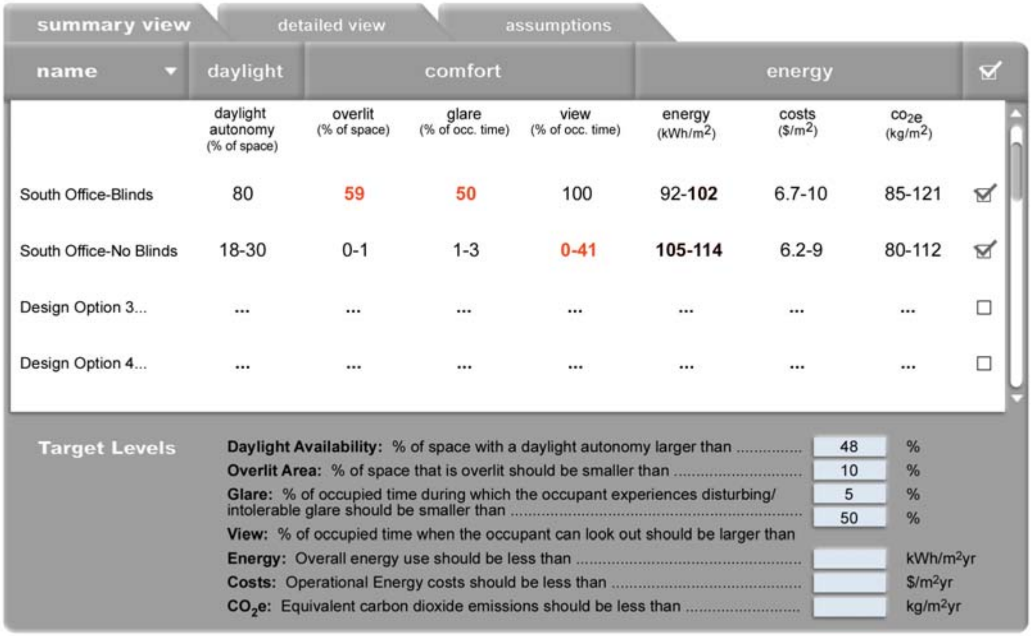


Figure 13: Daylighting Dashboard (comparative view).

Figure 13 shows that adding venetian blinds to the example space reduces the daylight area to a third or less of the space adjacent to the window but eliminates the overlit area. Intolerable glare now occurs less than 2% of the year but the blind blocks the view to the outside nearly 60% of the occupied times of the year. Overall thermal loads increase but energy costs and equivalent carbon emissions fall due to the high primary energy content of electricity compared to natural gas. All in all, the dashboard view suggests that adding external venetian blinds is necessary to take care of glare and also helps with energy considerations. Next logical steps would be to e.g. evaluate different shading devices and/or window sizes.

3.2 Multiple Spaces

The previous section showed that various design variants of a single space can be compared using the comparative daylighting dashboard view form Figure 13. But, that type of data display is still too complicated when one deals with the performance of many spaces in a building. At that point a different representation is needed that numerically summarizes the different performance metrics. The daylighting dashboard (summary view) in Figure 14 follows a Windows^{TM} File Manger type approach. Each space in a building is represented as a single row in which all daylighting metrics from Figure 13 are numerically displayed. Several variants of the same space, e.g. with and without blinds, are also possible. If a metric for a space lies outside of a user defined target range (lower part of Figure 14) this is flagged by a color code. Clicking on a metric column allows sorting the spaces accordingly. Using this type of display would allow a user to review the overall daylighting performance of multiple spaces in a very short period of time. An expert system could provide a list of potential design measures to address performance metrics that lie out of range. Simply clicking on several design variants could take a user to the comparative Daylighting Dashboard view form Figure 13. If desired, clicking on individual figures in Figure 13 could lead to even more detailed information for expert users such as temporal maps.



name	daylight	comfort			energy			☑
	daylight autonomy (% of space)	overlit (% of space)	glare (% of occ. time)	view (% of occ. time)	energy (kWh/m^2)	costs (\$/m^2)	co$_{2}$e (kg/m^2)	
South Office-Blinds	80	59	50	100	92-**102**	6.7-10	85-121	☑
South Office-No Blinds	18-30	0-1	1-3	0-41	**105-114**	6.2-9	80-112	☑
Design Option 3...	...	...	...	...	...	...	...	☐
Design Option 4...	...	...	...	...	...	...	...	☐

Target Levels

Daylight Availability: % of space with a daylight autonomy larger than .... 48 %
Overlit Area: % of space that is overlit should be smaller than .... 10 %
Glare: % of occupied time during which the occupant experiences disturbing/ intolerable glare should be smaller than .... 5 %
View: % of occupied time when the occupant can look out should be larger than 50 %
Energy: Overall energy use should be less than .... kWh/m^{2}yr
Costs: Operational Energy costs should be less than .... \$/m^{2}yr
CO$_2$e: Equivalent carbon dioxide emissions should be less than .... kg/m^{2}yr

Figure 14: Daylighting Dashboard (summary view).

4. Discussion

The proceeding sections provided an overview of the state of the art in computer-based daylighting analysis followed by an attempt to make the simulation results visually accessible to non experts and for complex buildings. The proposed solution is a multilayered data visualization platform that allows a software user to access daylighting related simulation results from the whole building level down to individual spaces and work places. This section discusses how such a design tool could be practically implemented using existing tools and technologies.

4.1 Relevance

This paper set out to develop a vision of where computer-based daylight performance analysis should be going. Figures 13 and 14 provide a blueprint for a daylighting design tool that provides design teams with relevant information regarding daylight availability, occupant comfort and energy. The authors believe that the information in the daylighting dashboard can be easily be explained to design decision makers including owners and architects and that these parties will find the information relevant enough to justify the costs required to generate them. The daylighting dashboard could also be an attractive tool to demonstrate compliance of a building with green building rating systems such as the US Green Building Council's LEED system and ASHRAE's new standard 189.1 for high performance green buildings (ANSI/ASHRAE/USGBC/IES 2010).

4.2 Defining Performance Targets

One aspect that sustainable design tools currently pay limited attention to is how to evaluate the simulation results. This does not imply that a design tool should 'tell' an architect how to design a building. But, a tool should offer a flexible module to declare design targets (see lower half of Figure 14) that allow a design team to implement their own, project specific design goals. The authors believe that this is an aspect where design software can empower its users and open up new venues for design exploration that add value to the overall simulation process. As an example, a tool should be able to accommodate specific requests such as 'for this space we want to avoid glare in the morning when it is used as a classroom but glare is less of a concern in the summer and during afternoons when the space acts as a daycare center'.

4.3 Simulation Effort

One important consideration for the usability of the above described simulation tool is what the required effort would be for a design team to carry out the simulations. The good news is that the information provided to carry out a fully integrated lighting/thermal analysis is already largely available in building information models. The four types of information required are scene geometry, materiality, thermal zones, intended program and schedules. As far as the authors know, all of this information with the exception of detailed schedules is already available in today's BIM software. One crucial piece that is further needed are extensive libraries that automatically populate all required inputs when a model is being built. Some software packages are already going that way (DesignBuilder 2010). Once all required input data has been assembled, the only required step is to export the data into specialized lighting and energy simulation software and to combine the output of the daylight simulations with an occupant behavior model and a thermal simulation engine (Figure 3).

4.4 Simulation Time

One severe practical concern, especially for daylight simulations, is that they tend to take a long time even though there is recent evidence that daylight simulation programs – even those that are using raytracing – can nowadays be carried a lot faster than in the past (Reinhart and Breton 2009). One obvious way to reduce simulation times and to free up individual users' CPU is to send simulation models to a simulation cluster for processing. This approach becomes especially appealing when a software can automatically generate and analyze several design variants in addition that the user defined base case. For example, given the poor glare performance of the base case from section 2 without blinds, the software could have automatically proposed and calculated the design variant with blinds. Such an expert system for daylighting was recently proposed by Lee, Andersen, Sheng and Cutler (Lee, Andersen et al. 2009).

4.5 Design Optimization

As mentioned above, a natural extension of the above sketched daylighting dashboard is to extend it with an expert system that – based on the target levels - provides comments on the results such as 'if a view to the outside is a concern for you, you might also want to consider the use of perforated shades'. Along with this advice, the software could automatically carry out the required design iterations so that the user can instantly review them.

5.5 Extension to Animations

Reviewing many different design alternatives one by one can be a tedious process. Data animations can help us to visually process many design alternations in series and to recognize complex patterns that would be difficult for a machine to resolve. Another possible extension of the daylighting dashboard is therefore to display performance data together with a geometric model in an animated building performance simulation (ABPS) (Lagios, Reinhart et al. 2010).

Summing up this paper has shown that today's computer-based daylighting analysis capabilities have reached a point at which daylight availability, occupant comfort, occupant behavior and energy use can be combined and presented to the user in a comprehensive performance dashboard that allows for the quick comparison of either a few or multiple design variants and spaces. The paper further argues that this approach is largely compatible with the current generation of building information modeling software and could hence be implemented in the medium to short term. Remaining obstacles are software interoperability issues between different simulation programs, simulation time and the identification of suitable targets ranges for the individual daylight performance metrics.

Acknowledgement

The writing of this paper has been supported by *Autodesk Architecture, Engineering & Construction*. The authors are indebted to Sian Kleindienst for providing the temporal illuminance map and Holly Wasilowski for generating the mockup dashboard views.

References

ANSI/ASHRAE/USGBC/IES (2010), "189.1 Standard for the Design of High-Performance Green Buildings", ASHRAE standard, Atlanta, GA, USA.

Bourgeois, D., C. F. Reinhart, G. Ward (2008), "A Standard Daylight Coefficient Model for Dynamic Daylighting Simulations", Building Research & Information **36**(1): 68 - 82.

BSI (2007), "BS EN 15251 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics", British Standard Institution, London, UK.

CHPS (2010), "Best Practices Manual", http://www.chps.net/, Collaborative for High Performance Schools (CHPS), San Francisco, CA, USA.

DesignBuilder (2010), "DesignBuilder V2", DesignBuilder Software Ltd (www.designbuilder.co.uk), Gloucestershire, UK.

EIA. (2010), "U.S. Energy Information Administration", from http://www.eia.doe.gov/.

Farley, K. M. and J. A. Veitch (2001), "A room with a view: A Review of the effects of windows on work and well-being", Research Report National Research Council Canada, IRC-RR-136: 1-33.

Frontini, F., T. E. Kuhn, S. Herkel; P. Strachan, G. Kokogiannakis (2009), "Implementation and application of a new bi-directional solar modeling method for complex facades within the esp-r building simulation program", Building Simulation 2009, Glasgow, UK.

Galasiu, A. and C. F. Reinhart (2007), "Current Daylighting Design Practice: A Survey", Building Research and Information **36**(2): 159-174.

Haldi, F. and D. Robinson (2009), "Interactions with window openings by office occupants", Building and Environment **44**(12): 2378-2395.

HarperCollins (2002), "Collins Thesaurus of the English Language - Complete and Unabridged", Second Edition, HarperCollins Publishers.

Ibarra, D. and C. F. Reinhart (2009), "Daylight factor simulations - How close do simulation beginners ‘really’ get?", Building Simulation 2009. Glasgow, Scotland, IBPSA**:** 196-203.

ICC (2010), "International Green Construction Code (Public Version 1.0)", International Code Council, Washington (DC), USA.

IESNA (2000), "IESNA Lighting Handbook", 9th edition, ISBN

0-87995-150-8, Illuminating Engineering Society of North America, New York, NY.

ISO (2003), "ISO 15099:2003 Thermal performance of windows, doors and shading devices - Detailed calculations", International Organization for Standardization , Geneva, Switzerland.

Kleindienst, S., M. Bodart, M. Andersen (2008), "Graphical Representation of Climate-Based Daylight Performance to Support Architectural Design", LEUKOS **5**(1): 39-61.

Kuhn, T. E. (2006), "Solar control: A general evaluation method for facades with venetian blinds or other solar control systems", Energy and Buildings **38**: 648-660.

Lagios, K., J. Niemasz, C. F. Reinhart (2010), "Animated Building Performance Simulation (ABPS) – Linking Rhinoceros/Grasshopper with Radiance/Daysim", SimBuild 2010, New York City, NY, USA, IBPSA-USA.

Lee, J., M. Andersen, Y. Sheng, B. Cutler (2009), "Goal-based daylighting design using an interactive simulation method", Building Simulation 2009. Glasgow, Scotland, IBPSA**:** 936-943.

Mardaljevic, J. (2000), "Simulation of annual daylighting profiles for internal illuminance", Lighting Research & Technology **32**(2): 111-118.

Mardaljevic, J. (2004), "Spatio-temporal dynamics of solar shading for a parametrically defined roof system", Energy and Buildings **36**: 815-823.

Mardaljevic, J., L. Heschong, E. Lee (2009), "Daylight metrics and energy savings", Lighting Research and Technology **41**(3): 261-283.

Marsh, A. (last accessed March 2010). Autodesk - Ecotect (version 5.6), Autodesk Inc.

Nabil, A. and J. Mardaljevic (2005), "Useful Daylight Illuminance: A New Paradigm to Access Daylight in Buildings", Lighting Research & Technology **37**(1): 41-59.

Nabil, A. and J. Mardaljevic (2006), "Useful Daylight Illuminances: A Replacement for Daylight Factors", Energy and Buildings **38**(7): 905-913.

Reinhart, C. and P.-F. Breton (2009), "Experimental Validation of 3ds Max® Design 2009 and Daysim 3.0", LEUKOS **6**(1).

Reinhart, C., J. Mardaljevic, Z. Rogers (2006), "Dynamic Daylight Performance Metrics for Sustainable Building Design", LEUKOS **3**(1): 1-20.

Reinhart, C. F. (2004), "LIGHTSWITCH 2002: A model for manual and automated control of electric lighting and blinds", Solar Energy **77**(1): 15-28.

Reinhart, C. F. (2005), "A simulation-based review of the ubiquitous window-head-height to daylit zone depth rule of thumb", Building Simulation 2005, Montreal, Canada, August 15-18.

Reinhart, C. F. (2010), "Simulation-based Daylight Performance Predictions", chapter in Building Performance Simulation for Design and Operation. J. Hensen and R. Lamberts, Taylor and Francis.

Reinhart, C. F. (last accessed Mar 2010). Daysim version 3.0 (http://daysim.com). Cambridge, MA, USA.

Reinhart, C. F. and O. Walkenhorst (2001), "*Dynamic RADIANCE-based Daylight Simulations for a full-scale Test Office with outer Venetian Blinds*", Energy & Buildings **33**(7): 683-697.

Rogers, Z. (2006), "Daylighting Metric Development Using Daylight Autonomy Calculations In the Sensor Placement Optimization Tool", Architectural Energy Corporation, Boulder, Colorado, USA, http://www.archenergy.com/SPOT/download.html.

Sze, J. L. (2009), "Indoor environmental conditions in New York City public school classrooms - A survey", Master in Design Studies Thesis, Harvard University, Graduate School of Design - Advanced Studies Program, Cambridge, MA, USA, pp. 1- 68.

US-DOE. (2010). "EnergyPlus V5.0." US Department of Energy, Building Technologies Program, from http://apps1.eere.energy.gov/buildings/energyplus/.

USGBC. (2009). "LEED-NC (Leadership in Energy and Environmental Design) Version 3.0." from www.usgbc.org/LEED/.

USGBC (2009). LEED 2009 for Schools. Washington DC, USA, US Green Building Council.

Ward, G. and F. Rubinstein (1988), "A New Technique for Computer Simulation of Illuminated Spaces", Journal of the Illuminating Engineering Society **1**: 80-91.

Ward, G. and R. Shakespeare (1998), "Rendering with RADIANCE. The Art and Science of Lighting Visualization", Morgan Kaufmann Publishers.

Wienold, J. (2007), "Dynamic simulation of blind control strategies for visual comfort and energy balance analysis", Building Simulation 2007, Beijing, China.

Wienold, J. (2009), "Dynamic Daylight Glare Evaluation", Building Simulation 2009, Glasgow (UK).

Wienold, J. (last accessed in March 2010). "Evalglare version 0.9f (www.ise.fraunhofer.de/radiance), Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany."

Wienold, J. and J. Christoffersen (2006), "Evaluation methods and development of a new glare prediction method for daylight environments with the use of CCD cameras", Energy and Buildings **38**(7): 743-757.