Easy-to-Implement Simulation Strategies for Annual Glare Risk Assessments based on the European Daylighting Standard EN 17037

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Abstract

This study presents a workflow that can be easily implemented in building simulation programs in order to perform annual glare risk assessments based on the Daylight Glare Probability (DGP) method. The DGP method has been used in the preparation of the European Daylighting Standard EN 17037 to recommend glare protection classes of shading devices for different situations (climate, façade orientation, window size, view position and direction). By implementing the DGP method, building simulation programs can be used to make design decisions on conflicting functions of fenestration systems, including glare protection. The DGP method requires detailed information about the optical behaviour of fenestration systems. Measurement procedures that are required to obtain the necessary optical information for glare protection fabrics are described here. The study also points to a new network of databases that offers accessibility and reliability for optical information in simulation software. A case study is presented to illustrate the proposed workflow.

Key Innovations

- Annual glare risk assessment based on timestep raytracing
- Measurement techniques to obtained required optical data for glare risk assessments
- Reliable and accessible representation of the optical behaviour of fenestration systems
- Sampling strategies to reduce the computational time of the simulation

Practical Implications

The trace-glare script (OSS) offers software developers and façade planners a computationally efficient approach to integrate annual glare risk assessments (according to EN 17037) into the design process for building façades.

Introduction

Visual comfort encompasses different aspects such as daylighting provision, view contact with the outside and glare protection (Kuhn, 2017). For these aspects, the European daylight standard EN 17037 (2018) recommends assessment criteria and procedures. The standard describes the current state of the art and should be taken into account during the design of building façades in Europe.

From the aspects covered in the standard, glare protection deserves particular attention. Glare occurs when too bright areas are located within the field of view or when the contrast ratio is reduced due to veiling reflections (EN 17037, 2018). There is a third critical situation when the contrast ratio in the field of view is reduced by small and intense light peaks (e.g. the solar disk viewed through a shading device). Shading systems or switchable fenestration systems are required to prevent glare due to daylighting. A glare assessment is suggested in spaces where the expected activities are comparable to reading, writing or using displays and the user is not able to choose his position freely (e.g. offices and classrooms). This assessment might not be necessary if the shading device has an opaque state and can be operated by the occupant (e.g. roller shutters and venetian blinds if there are no disturbing reflections between the slats in the closed position).

The perception of glare depends on the luminance distribution in the field of view and is therefore strongly affected by the position and view direction of the occupant. A direct view of the solar disk, mitigated or not by a semi-transparent shading device, or a direct view of its reflection from a specular surface are the dominant causes of glare in office-like spaces. Glare can also be caused by a view of intense diffuse reflection inside the room or outside the room through a window (e.g. direct solar radiation is reflected from a white wall).

In many situations, glare protection is mainly achieved by obstructing the view of the solar disk or its specular reflections. An occupant who is able to adapt her position and/or view direction will act accordingly. Still, in many cases, this is not possible. Frequent glare conditions in a space often trigger user reactions to the fenestration system, in the form of a formal or informal retrofit action (Fig. 1). A costly intervention can be avoided by appropriate glare risk assessment in the early phases of façade design.

Different types of fenestration systems require different glare assessment procedures. For fenestration systems where glare situations cannot be avoided (they are not opaque in the closed state), the standard proposes a simplified glare evaluation. This simplified evaluation is based on detailed glare simulations, which were carried out in preparation of the standard for a predefined set of building locations, façade orientations, room geometries, view positions and directions. Real situations, however, inevitably differ from the cases considered in the standard. This situation results in inaccurate glare risk assessments that are either too conservative or too risky, both with significant consequences in the façade design of buildings.

In this study, we propose simulation strategies that could be easily implemented in mainstream building simulation programs to allow annual glare risk assessments to be done reliably and efficiently. These simulation strategies are based on the open, raytracing software Radiance (Larson et al., 2005), but they can be adapted to other raytracers in the future, which e.g. take advantage of GPU acceleration.

Figure 1: Informal retrofit action in a classroom to prevent glare. A formal retrofit action, consisting of a reflective film applied to the exterior glass pane, had already been undertaken for the upper partition.

The Daylight Glare Probability metric

The standard recommends the Daylight Glare Probability (DGP) metric (Wienold and Christoffersen, 2006) to evaluate glare. In fact, a recent comparative study that involved 22 different glare metrics showed that the DGP is the most robust glare metric for office-like rooms under static conditions (Wienold et al., 2019). The DGP method captures the saturation effect from big glare sources (e.g. windows) and the reduction of the contrast ratio in the field of view.

A high level of glare protection for a given scene, view position and direction is accompanied by a low DGP value. For DGP values lower or equal to 0.35, daylight glare is considered imperceptible. DGP values higher than 0.35 and lower than 0.40 are associated with perceptible but usually not disturbing glare. When DGP values are higher than 0.40 and lower than 0.45, glare is perceptible and often disturbing. Finally, DGP values higher than 0.45 are considered intolerable.

The sun, as it moves across the sky throughout a day and throughout a year, reaches windows, indoor and outdoor surfaces with different incident angles. The glare phenomenon is intrinsically dynamic and has to be assessed as such. The standard defines an annual glare risk metric (fDGPt) as the percentage of discomfort glare hours when a DGP threshold is reached. The standard recommends glare protection measures when a DGP value of 0.45 is exceeded by no more than 5% of the reference usage time (DGP_e < 5%) (e.g. Monday to Friday, 8:00 to 18:00, throughout the year). DGP values have to be evaluated at the worst-case position in a room (e.g. close to a window).

The DGP metric can be obtained from the Radiance's *evalglare* program from a rendered luminance map of the field of view (.hdr image). Radiance's raytracing program, *rtrace*, can be used to generate luminance maps at a given position for a certain instant in time. For annual simulations, however, pure raytracing, timestep for timestep, has been considered to be too computationally expensive. Speedup strategies, such as the use of *rtrace* with null ambient bounces (-ab = 0) to generate luminance maps in combination with the calculation of the vertical illuminance at eye level, were used to approximate the DGP by the "enhanced simplified DGP" (eDGPs) (Wienold, 2009; Abravesh et al., 2019). As an alternative to timestep raytracing simulations, the five-phase method (Lee et al., 2018) pre-computes daylighting coefficients and then calculates luminance maps by matrix algebra for each sky condition. This approach recycles information from the scene in the dynamic simulations, saving computational time. Sepúlveda et al. (2021) show that timestep raytracing simulations, combined with optimized simulation parameters and a suitable sampling strategy, can be computationally more efficient than the five-phase method. In addition, the implementation and maintenance effort required by the Rtrace Method is considerably lower.

Limitations of the daylighting standard

Due to the opposing functions of fenestration systems, glare risk assessments are needed to balance glare protection against other functions such as daylight provision and viewing contact with the outside. For shading devices that do not have an opaque state, the standard proposes a simplified glare evaluation. The simplified evaluation is based on a comprehensive simulation study (similar to Wienold et al. (2017) and Chan et al. (2015)) for a side-lit office space with one façade. The simplified evaluation divides climatic conditions into two categories: those with high and those with low numbers of sunshine hours. It also classifies window sizes as large or small, and analyses three different distances from the observer to the opening and two different viewing directions. The method parametrizes shading devices in terms of their normal-normal transmittance, normal-diffuse transmittance and cut-off angle, assigning a glare protection class (from 0 to 4 according to EN 14501 (2020), where 4 is the best one) for every parameter combination. The result is look-up tables recommending a specific glare protection class for each climatic condition, window size, distance to the window and view direction. Tables are provided for different threshold values of DGP_e < 5% (0.45, 0.40, 0.35).

The resulting simplified method is very useful for quick checks but is inevitably inaccurate for situations different from those considered in the study. A detailed DGP simulation is advisable for an accurate glare risk assessment of a specific fenestration system as applied to a specific building.

A direct DGP simulation is, however, complex. It requires sufficient information about the optical behaviour of the fenestration system, computational capacity and expertise. At the time of writing this paper, mainstream building simulation programs offer limited methods for annual glare risk assessment (Table 1). The programs Ladybug/Honeybee (as plugin for Grasshopper/Rhino and Dynamo/Revit), COMFEN and IES are able to render images from view positions using Radiance and to derive luminance-based glare indexes for a few timesteps in a year. On the other hand, LightSolve and DIVA4Rhino implement detailed methods for calculating annual glare but do not support complex fenestration systems. All the other reviewed simulation interfaces did not offer state-of-the-art glare evaluation methods.

Table 1: Comparison of simulation interfaces in terms of glare risk assessment capabilities. DGI refers to the Daylight Glare Index.

Simulation interface	Simulation engine (Model)	Metric
IDA-ICE	None	None
AERCalc	None	None
COMFEN	Radiance (raytracing)	DGI
Open Studio	None	None
LightSolve	Own raytracer (graphic acceleration)	DGP
DIALlux-EVO	None	None
DIVA for RHINO	Daysim,Radiance (Daylight coeff., raytracing)	Enhanced simplified DGP
IES	Radiance (raytracing)	CIE Glare Index DGP
Ladybug/Honeybee	Radiance (raytracing)	DGP
Design Builder	EnergyPlus	EnergyPlus glare index

Proposed method

The simulation strategies presented in this paper have been implemented in the trace-glare script (OSS) (Bueno, 2020b). This script allows annual glare risk assessment based on the DGP method. The tool uses a direct DGP calculation based on timestep raytracing simulations with Radiance (the Rtrace Method). The required information of the shading device is a Bi-directional Scattering Distribution Function (BSDF) dataset in Klems format (Geisler-Moroder et al., 2021). This information is then combined with a peak-extraction algorithm as described below. The measurements required to obtain the BSDF dataset are also indicated in this section. In addition, the study describes a knowledge database that is being developed to efficiently retrieve characteristics of fenestration systems such as BSDF. A case study is worked out to illustrate the proposed method.

Case study

The Z3 building in Stuttgart is the new headquarters of the construction company Ed. Züblin AG (Bezler, 2015). The façade is composed of a multi-layer wood structure, which provides the architectural signature of the building. Fig. 2 shows a rendering of one of the rooms of the Z3 building, the object of the study. The room has two main facades facing west and north. Window elements are equipped with triple-pane insulating glazing units and provided with individually movable, internal glare-protection roller blinds. The viewing positions and directions analysed in this case study are indicated in Fig. 3. View directions are oriented parallel and 45° respect to the west façade, which is the main glare source.

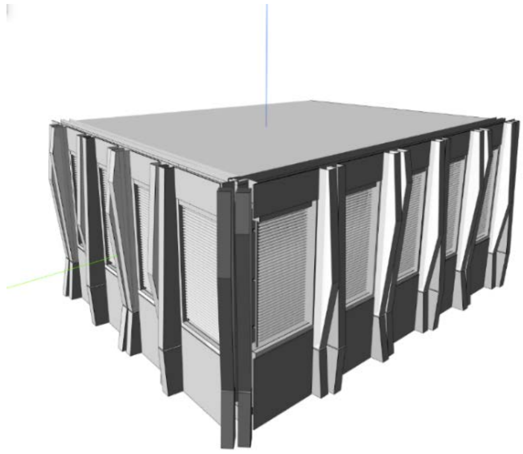

Figure 2: Rendering of the room, object of the study. Source of Radiance information: Ed Züblin AG

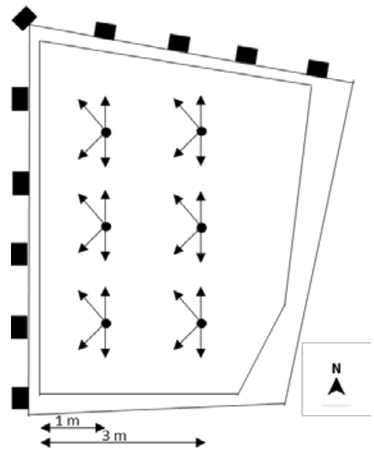

Figure 3: Plan view of the room, indicating view positions and directions.

Choosing a glare protection device

By applying the simplified glare evaluation, the standard recommends shading devices with different glare protection classes between 1 and 3, depending on view directions and positions. Table 2 indicates the recommended glare protection classes of fabrics for a Sunshine Zone L (Germany), a west orientation and a large opening. The chosen metric is the least restrictive one, DGP_e< 5 % (DGP <= 0.45).

Table 2: Recommended glare protection classes of fabrics for a Sunshine Zone L (Germany), a west orientation and a large opening, depending on the view direction (parallel and 45° with respect to the window) and the distance between the observer and the façade.

Distance to the façade	Parallel view direction	45° view direction
1 m	2	3
2 m	1	3
3 m	1	2

A designer who wants to make use of most of the space in the room should pick the most restrictive glare protection class (class 3). Two candidates of glare protection fabrics are presented in Table 3.

Table 3: Glare protection fabrics used in the analysis. The main values indicated are those determined with integrating spheres as specified in EN 14500:2020. The values in parentheses were determined by spatial integration of visible BSDF data, taking a half-angle of 5 ° to distinguish between "normal" and "diffuse" emergence.

	Fabric A	Fabric B
Normal-normal visible transmittance	1.8 % (2.0 %)	1.6 % (1.5 %)
Normal-diffuse visible transmittance	1.2 % (1.3 %)	0.4 % (0.4 %)
Glare protection class	3	3

By applying the proposed workflow, the designer can make an informed decision on the selection of the glare protection device for the room.

Optical characterization

Special attention must be paid to the optical representation of fenestration systems in the raytracing model.

The simplest type of experimental optical characterization for this type of fabric provides the normal-normal and normal-diffuse transmittance values, as documented in Table 3. These values are determined most commonly from measurements of the normal-hemispherical and normal-diffuse transmittance with integrating sphere accessories to spectrophotometers for the visible range. The normal-normal transmittance is then determined as the difference between normal-hemispherical and normal-diffuse transmittance. As has been documented in the recently published EN 14500 (2020) standard and the NFRC document NFRC 300:2017-E0A2, care has to be taken that the measurement beam samples a representative area of the sample, and that all of the light that is transmitted by the sample is actually captured by the integrating sphere, so that the normal-hemispherical transmittance value is accurate. As the normal-diffuse transmittance is determined by allowing the "normal-normal" fraction of the radiation to exit the sphere through an aperture, the determined value depends on the solid angle which this aperture defines. The EN standard and NFRC document cited above limit the range of permissible solid angles by specifying allowable ratios of the exit aperture area to sphere surface area.

Shading devices scatter light differently for different incoming light directions. This angle-dependent optical behaviour can be represented by a BSDF. In this representation, the hemispheres on both sides of a fenestration system are discretized into regions, which might have different solid angles. A BSDF dataset is then composed of coefficients, for each pair of incoming and exiting light directions, which specify the amount of radiance incident from one direction that is transmitted into the exiting direction.

BSDF data can be calculated from the normal-normal and normal-diffuse transmittance in combination with sample models of various degrees of sophistication (Wienold et al., 2017; Tzempelikos and Chan, 2016) or they can be measured directly with a photogoniometer, which can be based on a 3D-scanning detector or image-processing of a wide-angle image. The 3D-scanning photogoniometer offers the advantage that the detected transmitted rays are always normally incident on the detector surface. The spatial sampling rate can also be programmed to be higher in order to capture light peaks (Apian-Bennewitz, 2010).

It should be noted that the transmittance values that are required for the best glare protection class according to EN 14501 (e.g. requiring normal-normal transmittance ≤ 0.01 in combination with normal-diffuse transmittance ≤ 0.03) are very low compared e.g. to the tolerances that are specified for submission of data measured with integrating spheres for non-scattering glass panes to the IGDB, i.e. 0.01 for normal-hemispherical transmittance and 0.02 for near-normal reflectance. The accuracy of the measurement instruments themselves is certainly better than this, as has been documented by various interlaboratory comparisons conducted by NFRC or ICG-TC10, but the values measured for a given sample will be accurate to the necessary extent *only* if the precautions specified in EN 14500 (2020) and NFRC 300:2017-E0A2 are taken. Explicit consideration of the "dark signal" is also important when such low values are to be determined experimentally; this is standard practice for spectrophotometric measurements but should also be implemented for photogoniometric measurements. If such precautions are taken, a tolerance of 0.005 can be achieved with both types of instruments.

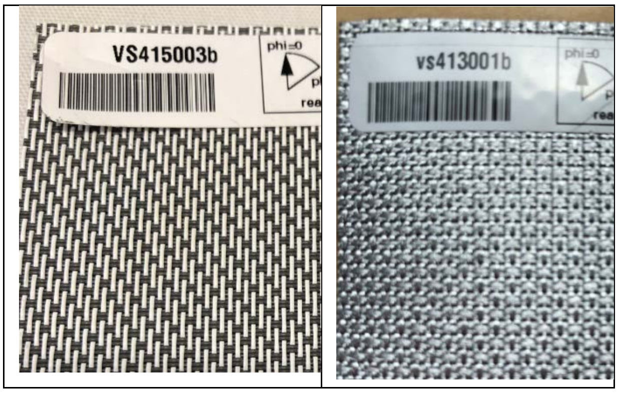

Figure 4: Outdoor-facing surfaces of measured samples from fabric A (left) and fabric B (right). The labels with dimensions of 38 mm x *13 mm give an indication of scale.*

Samples of the fabric A (EuroTwill 6216 slate) and the fabric B (Verosol EnviroScreen) (Fig. 4) were optically characterized by the TestLab Solar Façades at Fraunhofer ISE. BSDF data for these fabrics was measured with the pg2 photogoniometer from pab-opto at incidence angles in degrees of

theta = [0°, 8°, 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°]

phi = [0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°]

As is documented in Table 3 for the case of normal incidence, additional measurements with integrating spheres verified the photogoniometer measurement results that had been corrected with the measured dark signal.

The interpolation algorithms offered by Radiance were applied to obtain scattering functions for different incidence angles than those measured. These programs (Radiance's *pab2opto*, *bsdf2ttree* and *bsdf2klems*) convert the resulting data points into the desired format.

Representation of light peaks in the model

As previously mentioned, the DGP calculation is very sensitive to the light peaks produced by direct optical transmission of the sunrays through the fenestration system or by specular reflections on its surfaces. Due to the relatively large solid angle of the Klems format, this is not adequate to represent peaks, resulting in an underprediction of the DGP value when these peaks occur (e.g. the solar disk is in the field of view).

One attempt to resolve light peaks correctly in a DGP simulation is to increase the resolution of BSDF data for the angular regions where peaks occur. A tensor-tree formalism, such as the one supported by Radiance (Ward et al., 2012), can be used for this purpose. For this formalism, the maximum resolution of the tensor-tree is controlled by the exponent n of peak resolution (e.g. n = 6 corresponds to a peak resolution of 2^6 (64) in each dimension).

As an alternative to the increase in BSDF angular resolution, one can treat light transmittance peaks independently from the rest of the BSDF dataset. The peak extraction algorithm implemented in Radiance ("aBSDF" material type (Ward 2020)) is used to identify peaks in the undistorted direct-through direction of a BSDF. Based on this, the "vision" component and the non-scattered, directly transmitted solar component can be separated in the simulation.

Sepúlveda et al. (2021) show that a DGP calculation of a fenestration system with a dominant view-through direct transmittance can be performed representing the façade by a low-resolution anisotropic Klems BSDF combined with the peak extraction algorithm provided by the Radiance Software.

Access to reliable BSDF datasets

A glare simulation requires a BSDF of the fenestration system. In many cases, a fenestration system is composed of a glazing unit and a shading device. Manufacturers of shading devices can optically characterize their products by measurements with a photogoniometer (see previous section). However, a BSDF of a combination of a glazing unit and a shading device has to be derived numerically (Bueno et al., 2017). Tools such as the LBNL's WINDOW software (LBNL, 2020) and Fener (Bueno, 2020) offer the Klems method (Klems, 1994) for this purpose. The Klems method can be applied to generate a BSDF of a glazing unit and a shading device from the individual BSDF datasets. However, this method is only available for BSDF formalisms with fixed angular discretizations (e.g. Klems), which excludes tensor-tree BSDF formalisms.

Access to reliable BSDF datasets is still an issue for designers and software providers. The International Glazing and Shading Database (IGSDB) is under development as the successor to the popular databases International Glazing Database (IGDB) and Complex Glazing Database (CGDB). At the same time, buildingenvelopedata.org will be established as a meta-database to manage the metadata of building envelope components and to offer a search function.

Ongoing research aims to develop a "network of databases" which will improve the access to reliable BSDF data (Maurer et al., 2021). Through application programming interfaces (API), the "network of databases" will e.g. be able to query the meta-database for BSDF data in IGSDB and further databases. It will also offer the possibility to approve datasets with a digital signature. The approvals can be used to select BSDF data sets from approvers with high quality standards.

Model set-up

The *trace-glare* tool calls Radiance's *rtrace* in order to generate a luminance map of the field of view for a selected number of timesteps in a year. Each luminance map is then processed by Radiance's *evalglare* to calculate a DGP value for these timesteps.

In order to force the simulation, the scene to be analysed (i.e. room geometry) must be provided in Radiance format. The scene must include neighbouring buildings that can cast shadows onto the room, as well as the reflectance of its surfaces, differentiating between specular and diffuse reflectance. Many tools can be used at this stage to convert geometries of a specific format (e.g. ifc) into a Radiance geometry. The next step is to define the view positions and directions to be analysed. For the proposed method, where glare simulations are performed only for clear skies, a weather file is not necessary. It is sufficient to provide the longitude, latitude and time zone of the building location.

Dynamic calculations

To obtain the annual glare metric (fDGPt), the DGP calculation of the scene has to be repeated for every daylighting hour of the year. An annual simulation for all daylighting hours can take weeks and is not affordable in many cases.

Since only sunny skies need to be considered in the glare evaluation, the simulation of only half of the year (from the winter to the summer solstice) already provides all solar positions in the sky and reduces the computational time by half. A further reduction of the computational time can be achieved by applying a sampling strategy. Sepúlveda et al. (2021) illustrates the relationship between computational cost and accuracy in fDGPt calculation for different sampling strategies. For comparing the fDGPt metric between systems with a low normal-normal transmittance, simulating one day a week is considered appropriate. Another sampling strategy consists of simulating only the time steps where the solar disk is in the field of view. This strategy assumes that no diffuse and/or specular reflections of the sun from any surface of the scene or the shading device will cause glare when this is not in the field of view, which is a reasonable assumption in many cases.

To check whether, for a certain scene, the solar disk is in the field of view, a preliminary and fast *rtrace* calculation with null ambient bounces (-ab 0) can be performed. If the resulting illuminance is below a threshold, the solar disk is assumed not to be in the field of view and the glare index is set to imperceptible for that timestep.

Results of the case study

In our case study, the designer wants to select the most suitable glare protection fabric for the room. At this point, BSDF datasets in Klems format of the two candidate fabrics have been obtained through optical measurements or accessed through a database. These BSDF must then be combined with the triple-pane insulating glazing unit planned for the room. The BSDF of a combination of a fabric and a glazing unit is generated with the Klems method (Klems, 1994) implemented in Fener (Bueno, 2020).

Simulations with the *trace-glare* tool are carried out for the sensor points indicated in Fig. 3 and for the two glare protection fabrics. Fig. 4 shows the results of the simulations, indicating the view positions and directions in which there is a glare risk (fDGPt is greater than 5%). Two levels of glare risk are shown, DGP_e < 5% = 0.45 (red) and DGP_e < 5% = 0.40 (orange).

The results for the fabric A show a high glare risk for all view positions considered if the view direction is pointing 45° towards the window. Medium glare risks are obtained for the view positions close to the window for parallel view directions. For view positions further away from the window and parallel view directions, no glare risk is observed.

The results for the fabric B indicate a lower glare risk than for the fabric A. Similar results are obtained for the view positions close to the west window. However, further away from the window, only medium glare risk is obtained for view directions at 45° except for one position close to the north window.

Based on these results and the expected use of the room, the designer can make an informative decision on which glare protection device to select. In this case, glare protection should be considered together with other façade functions such as daylighting and view contact with the outside.

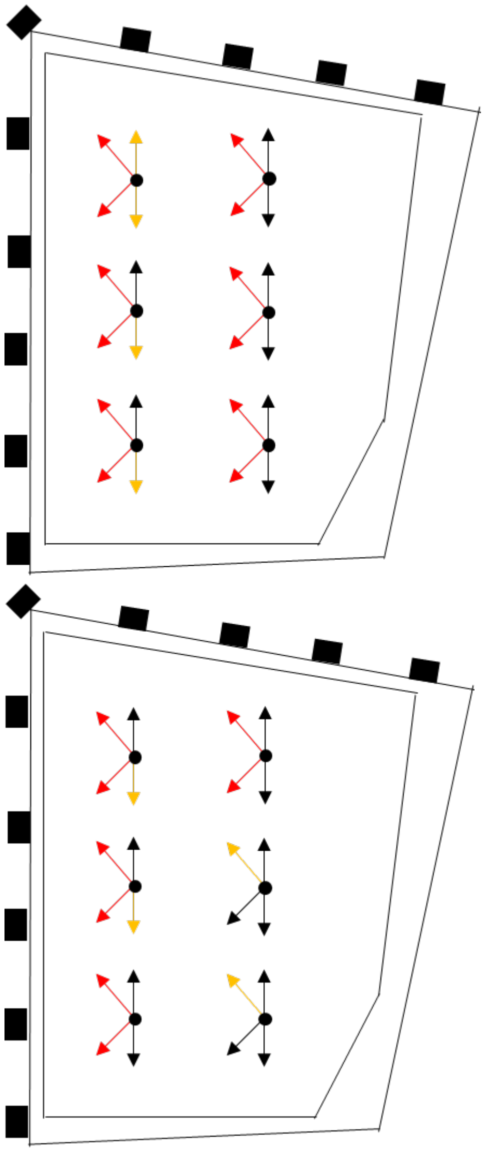

Figure 1: Plan view of the room indicating the view positions and directions in which fDGPt is greater than 5%. The following thresholds are considered: (red) DGP_e = 0.45, (orange) DGP_e = 0.40. (upper) Simulation results for the fabric A. (lower) Simulation results for the fabric B.

Conclusion

A workflow is presented to perform annual glare risk assessments based on the EN 17037. This workflow has been implemented in a script, *trace-glare* (OSS), which can be integrated in building simulation programs in order to perform annual glare risk assessments. The script contains commands for the OSS Radiance, a validated raytracing tool. Optimized Radiance parameters for glare calculations are included in the script. A computationally efficient sampling strategy is also provided. The raytracing engine is called for the hours of the day in which the solar disk is in the field of view. One day per week for a semi-annual period is simulated, although more frequent simulations (e.g. one-day simulation every five days) might be advisable for other case studies. The workflow requires a Radiance description of the scene and BSDF datasets in Klems format of the fenestration system. The proposed workflow is subject to two main assumptions, viz.

- The application of Radiance's peak extraction algorithm assumes that the fenestration system has a dominant view-through direct transmittance without light redirecting effects.
- The sampling strategy assumes that no diffuse and/or specular reflections of the sun from any surface of the scene or the shading device will cause glare when this is not in the field of view.

Future work will implement these simulation strategies in a rendering engine that takes advantage of state-of-art acceleration techniques (e.g. vectorization or GPU acceleration). The resulting tool should allow interactive exploration of glare risk throughout a building by using popular building design environments.

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