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ANNUAL EVALUATION OF DAYLIGHT DISCOMFORT GLARE: STATE OF THE ART AND DESCRIPTION OF A NEW SIMPLIFIED APPROACH

Luigi Giovannini et al.

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CIE Central Bureau
Babenbergerstrasse 9
A-1010 Vienna
Austria
Tel.: +43 1 714 3187
e-mail: ciecb@cie.co.at
www.cie.co.at

ANNUAL EVALUATION OF DAYLIGHT DISCOMFORT GLARE: STATE OF THE ART AND DESCRIPTION OF A NEW SIMPLIFIED APPROACH

Giovannini, L.[1], Favoino, F.[1], Lo Verso, V.R.M.[1], Pellegrino, A.[1], Serra, V.[1]
[1] Politecnico di Torino, Department of Energy "Galileo Ferraris", Technology Energy Building Environment (TEBE) Research Group, Torino, ITALY

luigi.giovannini@polito.it

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Abstract

A simplified approach that was developed for annual daylight glare analyses in buildings is presented. The approach enables to classify a whole space in terms of daylight glare comfort classes (imperceptible glare, perceptible glare, disturbing glare and intolerable glare) through the eye vertical illuminance, and it was validated against DGP values. The approach allows a significant reduction of the computation time required for annual glare analyses. Potentials and drawbacks of the simplified method are critically discussed, also with respect to other simplified approaches defined by other authors in the past.

Keywords: daylight glare, annual glare evaluation, DGP, daylight simulation, visual comfort

1 Introduction

The daylight discomfort glare in a space is a complex phenomenon which plays a key role in determining the occupant's visual comfort and can affect people performance and well-being. Furthermore, the glare produced by daylight sources is one of most recurrent causes for the activation of shading systems, the use of which can affect both the indoor environmental quality and the energy performance of a space. In spite of its importance, daylight discomfort glare is not so often considered and assessed during the design phases or, in most cases, it is only indirectly evaluated through the incident radiation or illuminance on the façade or on the workplane. However, all these approaches may eventually result quite inaccurate in the estimation of such a complex phenomenon. The glare phenomenon, which has both a temporal and a spatial variation, is a function of the user's position and direction of view and it is determined by the dynamically changing luminance of the sky dome. Moreover, it is influenced by material properties and geometrical aspects (i.e. window and room surfaces optical properties; presence and features of moveable shading devices etc.), which makes the evaluation of annual daylight glare even more complex (Chiaraviglio, 2009).

A number of different glare indices was proposed in the past to quantify the discomfort glare potentially perceived by building occupants. The first attempt to quantify glare from daylight was the "Daylight Glare Index" (DGI) (Hopkinson, 1972), which had the merit to introduce in its equation all the main factors potentially concurring in the determination of a glare condition from daylight: luminance and solid angle of the light source, average luminance of the background, position of the light source relative to the observer's field of view. However, DGI showed a low reliability as a glare predictor in presence of windows, especially when these occupy most of the observer's field of view, or when the sun is in the occupant's visual field (Iwata *et al.*, 1992b, 1992a; Waters, Mistrick and Bernecker, 1995). To simplify the calculation of the daylight glare, attempts were also made to estimate it by using the vertical illuminance at the observer's eyes, in replacement of the background luminance (Velds, 1999). For a more general insight, a critical overview of the first glare indices is reported in (Osterhaus, 2005).

A new metric was introduced by Wienold and Christoffersen (Wienold and Christoffersen, 2006), namely the Daylight Glare Probability (DGP), which expresses the percent of occupants disturbed by a daylighting glare situation. DGP is calculated according to the following equation:

$$\mathrm{DGP} = 5.87 \cdot 10^{-5}\, \mathrm{E_v} + 9.18 \cdot 10^{-2} \log\left(1 + \sum_i \frac{\mathrm{L_{s,i}^2}\, \omega_{\mathrm{s,i}}}{\mathrm{E_v^{1.87}}\, \mathrm{P_i^2}}\right) + 0.16 \tag{1}$$

where E_v is the vertical illuminance at eye level [lx]; L_s is the light source luminance [cd/m^2], ω_s is the light source solid angle [sr]; P is the position index [-]. The equation consists of two terms: the first one considers the vertical eye illuminance, while the second accounts for the contrast between the scene background luminance and the luminance of the light sources within one's visual field. The index was validated against a thorough set of experimental measures in real office rooms and was then implemented in the lighting calculation engine Radiance (*Radiance*, no date), through the purposely-developed tool Evalglare (*Evalglare*, no date).

Besides, the evaluation of daylighting in buildings has moved towards the so-called climate based daylighting modelling (CBDM) (Reinhart, Mardaljevic and Rogers, 2006; Mardaljevic, 2008), which is aimed at providing results representative of a long-term analysis (generally one year). An annual DGP analysis is far time consuming, as it requires an high dynamic range (HDR) image to be generated for each time-step (typically an hour) considered during the course of a year. Furthermore, the DGP depends on the view direction and position in the space, meaning that to assess the daylight glare condition occurring throughout a space the DGP calculation should be repeated for several relevant points and view directions in the space considered.

Different approaches to allow faster annual glare analyses were proposed in the past. Among them, two simplified methods were introduced by Wienold. The first one is the *enhanced simplified Daylight Glare Probability*, which uses a simplified rendered image for every time-step of the year. This image accounts for the luminance of the main glare sources alone, without considering the exact luminance distribution within the room (Wienold, 2009). This solution allows a significant reduction in the computation time, as light inter-reflections are not accounted, but may present an underestimation problem in the presence of materials with a low visual transmission, translucent materials or materials that scatter the transmitted or reflected light. The enhanced simplified DGP proved to have a good correlation with DGP, therefore it was implemented in Radiance to allow faster annual glare simulations. The second simplified method is the *DGPs* (Wienold, 2007), which was conceived with the aim of excluding the luminance contrast component from the glare evaluation, hence further reducing the computational effort required. The DGPs is in fact calculated from the eye vertical illuminance alone, which was correlated to DGP through a linear equation. Despite the DGPs allows faster annual evaluations (as it does not require an image to be generated for each time-step), it showed a good correlation with the DGP only for conditions when direct sunlight or highlight reflections are not present in the scene.

Besides the attempts to develop methods to evaluate glare sensation or probability, some metrics were also introduced to assess the risk of discomfort due to over-lighting in the frame of the CBDM approach. They are based on the annual workplane illuminance, which gives several advantages in terms of computation time. Two metrics estimate the percentage of occupied time for which a potential glare condition, corresponding to global illuminance over a threshold value, occurs in a point (DA_{max} (Reinhart, Mardaljevic and Rogers, 2006) and $UDI_{exceeded}$ (Nabil and Mardaljevic, 2005)), while a third metric (Annual Sunlight Exposure – ASE) considers the percentage of space with a direct illuminance from the sun over a threshold value (1000 lux) for more than a certain amount of time (250 hours) over the year (IES Daylight Metrics Committee, 2012).

Currently, the most reliable and validated metric to assess glare from daylight is the Daylight Glare Probability (DGP). This enables assessing both the influence of direct illuminance at the eye level and of the luminance contrast in the determination of the final glare condition. However, as highlighted above, the calculation of the DGP, and particularly of the contrast term in the equation, requires an HDR image to be rendered at each time-step, which results in a high computational time to perform an annual analysis. Consequently, this metric is typically assessed for one or few significant points within the space, with the risk of inaccurately represent the different glare conditions occurring throughout the whole space (especially for large spaces).

In this framework, the paper presents a study carried out to define a new simplified and fast approach for the estimation of the annual glare condition in interiors, with high spatial resolution. This is based on the calculation of the eye vertical illuminance (E_v), which is assumed as parameter to define the daylight glare class of any point in the space. The accuracy of the method was determined through the comparison with DGP values by applying a fault-detection technique. A preliminary paper that describes the study was published by the same Authors (Giovannini *et al.*, 2018). In this paper the results of an expanded study are presented: in this the new simplified approach is tested for a larger number of viewpoints and, for each viewpoint, considering a plurality of view directions.

2 A novel method for annual spatial glare analyses

The aim of the simplified method proposed in the study is to allow the evaluation of an entire space in terms of daylight glare comfort classes, for a whole year, with a reduced computation time compared to a comprehensive and accurate annual glare assessment through the Daylight Glare Probability (DGP).

The development of the new method was based on three main simplification assumptions:

- to use the eye vertical illuminance (E_v) as the only variable to estimate the daylight glare condition;
- to express the daylight glare condition in terms of daylight glare comfort classes rather than through the exact DGP value;
- to calculate the DGP for a single point in order to estimate afterwards, through the vertical illuminance at the eye level, the daylight glare comfort classes for all the points in the space.

The calculation of the eye vertical illuminance, without considering the luminance of the light sources and the luminance contrast in one's field of view, results in a significant reduction of the required computation time, although it could introduce some inaccuracies in the assessment, as the contribution of the luminance contrast to glare sensation is neglected.

The idea of describing the glare sensation through classes was originally proposed by Hopkinson, who divided the glare sensation range in four classes: "Just Perceptible", "Just Acceptable", "Just Uncomfortable" and "Just Intolerable". This approach was also adopted by Wienold for the DGP metric: specific ranges of DGP values were associated to different glare sensations (Wienold, 2009). The following daylight glare comfort classes were introduced and for each class, a DGP threshold value (DGP_{thr}) was defined: *imperceptible* glare (DGP < 35%), *perceptible* glare (35% ≤ DGP < 40%), *disturbing* glare (40% ≤ DGP < 45%), *intolerable* glare (DGP ≥ 45%).

To define the new simplified method and to verify its robustness and accuracy with respect to a DGP-based comprehensive annual glare assessment, a simulation study was developed. The approach adopted in the study consisted of three steps:

- ***step 1:*** aimed at determining the vertical illuminances to be assumed as thresholds for each daylight glare comfort class ($E_{v,thr}$). Once the $E_{v,thr}$ values are defined, the E_v calculated for each point and view direction in the space can be used to classify the glare condition according the corresponding daylight glare comfort class;
- ***step 2:*** aimed at quantifying the errors committed in the estimation of the daylight glare comfort class when the $E_{v,thr}$ of a single point is assumed to define the daylight glare comfort class thresholds of all other points in the space, with respect to the classification obtained using the exact DGP values;
- ***step 3:*** aimed at identifying of the most suitable point (or points) in the space and direction of view for the calculation of the E_v thresholds to be adopted to classify the whole space according to the daylight glare comfort classes.

It is worth noticing that the accuracy of this simplified approach also depends on factors such as shape, size and orientation of the space considered, view direction with respect to the daylight source (window), geometric and optical properties of windows and solar shadings. The study is a first evaluation of the suitability of the simplified approach, which was applied to a case-study as described in the next section.

2.1 Application to a case study

The three steps of the approach were applied to a single cellular office that was 3.6 m large, 6 m deep and 2.7 m high. The office had a single window 3.3 m wide and 1.5 m high. The office was assumed as located in Turin (45.06° N, 7.68° E) and simulations were repeated so as to have the window facing South and West, and for several window configurations. In fact, windows were assumed as equipped with glazing with different transmission properties (specular or scattering) and different visible transmittances (T_v), for a total number of 16 glazing types. The scattering glazing was considered as Lambertian. The following T_v values were assumed, for both the specular and the scattering glazing: 0.05, 0.15, 0.25, 0.35, 0.45, 0.55, 0.65, and 0.75. Additionally, two shading devices were considered, both applied to the specular glazing with T_v = 0.75. These are venetian blinds (VB) with three different slat angles: 0° (horizontal), 30°, 60°; and roller blinds (RB) with two different T_v values: 0.04 (typical value of a blind for glare control) and 0.15 (typical value of a blind for solar control). The VB slats have a depth of 3.5 cm, and were modelled as a plastic material with a visible reflectance (R_v) of 0.44, while RBs were modelled as a Lambertian translucent material.

The following visible reflectances were assumed: 0.80 for the ceiling, 0.65 for the walls, 0.35 for the floor, and 0.10 for the albedo. A 3x3 grid of points across the room was identified. The points are 1.2 m high and five view directions were chosen to cover the more probable directions that can cause glare (see Figure 1).

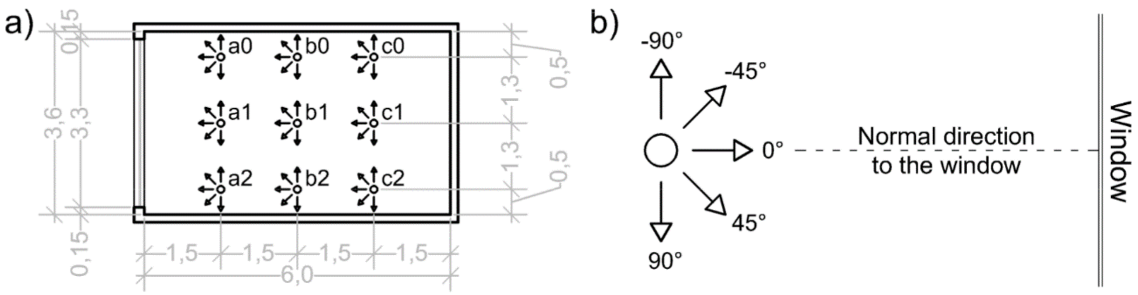

Figure 1 – a) Plan view of the office, with the location and view directions for all the points considered; b) directions of observation assumed, in respect to the normal to the window.

Annual DGP and E_v values for each point and each view direction were calculated through DAYSIM software (*DAYSIM*, no date). To calculate the annual DGP profiles, DAYSIM uses the enhanced simplified DGP method described in (Wienold, 2009), for which DGP is still evaluated through equation (1), where the second term of the equation, i.e. luminance contrast, is calculated analysing a simplified image (less time-consuming) in which the main luminance sources in the scene only are accounted. The following simulation parameters were set: ab=5, ad=1024, as=128, ar=300, aa=0.1. Simulations were performed with a time-step of 1 hour, considering the annual daylight hours in Turin only (4602 h). This operation was repeated for every glazing type and shading device considered, as well as for both S and W orientations. The simulation outcome was an annual database for each glazing and shading type, containing for each timestep of the year a pair of values for every view direction relative to each of the 9 points: a DGP value and an E_v value. These results were post-processed, according to the 3 steps of the approach.

2.2 Step 1: determination of the E_v thresholds

The first step is aimed at defining the most suitable E_v values to be used as thresholds for each daylight glare comfort class. As four glare comfort classes are identified, three E_v thresholds need to be calculated: the lower threshold, between imperceptible and perceptible glare (DGP=35%); the intermediate threshold, between perceptible and disturbing glare (DGP=40%); the upper threshold, between perceptible and intolerable glare (DGP=45%).

For each point of the grid, view direction, window configuration and orientation, the calculated E_v and DGP were correlated, and the E_v values to be used as threshold between the glare comfort classes were identified through a fault-detection technique. The fault-detection analysis allowed selecting the threshold values ($E_{v,thr}$) minimising the errors committed when estimating the daylight glare comfort classes through the vertical illuminance. In fact, comparing the calculated hourly DGP and E_v values, four scenarios can occur:

- True Positive Estimation (TP): when $E_v > E_{v,thr}$ and $DGP > DGP_{thr}$
- True Negative Estimation (TN): when $E_v < E_{v,thr}$ and $DGP < DGP_{thr}$
- False Positive Estimation (FP): when $E_v > E_{v,thr}$ and $DGP < DGP_{thr}$
- False Negative Estimation (FN): when $E_v < E_{v,thr}$ and $DGP > DGP_{thr}$.

While TP and TN results represent a correct estimation of the daylight glare comfort class ("True" estimation), FP and FN scenarios represent a "False" estimation (and hence error), as they show a discordance between the estimation of a glare/non glare condition performed through E_v with respect to the one carried out by means of the DGP.

For each point, view direction, window configuration and orientation, the three $E_{v,thr}$, which define the four glare comfort classes, are identified as the ones minimising the number of FP+FN occurrences. A total number of 1890 $E_{v,thr}$ triplets was obtained (21 window configurations x 9 points x 5 view directions x 2 orientations = 1890 $E_{v,thr}$ triplets).

2.3 Step 2: estimation of the errors committed using one point for spatial analysis

After defining the 1890 $E_{v,thr}$ triplets, the second step consisted in calculating the magnitude of the error committed when the $E_{v,thr}$ triplet determined for a single point and view direction is used to calculate the daylight glare comfort class of all the other points (with the same view direction). The error was expressed as percentage of occurrences of FP+FN estimations over a year with respect to the estimation performed with the exact DGP values. The result was a triplet of errors for each grid point (one error for each $E_{v,thr}$) for a total number of 1890 triplets.

This step of the procedure was functional to enable the estimation of the daylight glare comfort classes in the whole space using the $E_{v,thr}$ calculated for a single point, meaning that a single annual DGP profile has to be calculated.

2.4 Step 3: identification of the most suitable points for spatial analysis

The aim of the last step was the identification of the most suitable point(s) – view direction(s) in the space to be used to estimate the daylight glare comfort classes for all the points. This allows a space to be classified according to daylight glare comfort classes, by evaluating the annual DGP, and the relative $E_{v,thr}$ triplet, for one point only.

The 95% percentile error was quantified for each point and view direction. This was expressed as percentage of FP+FN occurrences over a year and represents the maximum error committed in 95% of cases. In addition, for each point and view direction, the number of cases for which the calculation of an $E_{v,thr}$ value was possible was quantified as well. Finally, the most suitable combination *point-view direction* was found as the one maximising the total number of cases for which it was possible to calculate the $E_{v,thr}$ values while minimising the maximum error committed for 95% of time. It is possible that the maximisation of the first aspect and the maximisation of the second do not occur for the same combination. In this case, depending on the number of cases for which $E_{v,thr}$ values were calculated and on the 95th percentile maximum error value, two different most convenient points for the calculation of the only DGP profile may be defined.

3 Results

The results obtained from the application of the approach to the case study are presented with regard to each step of the approach. The analysis was performed for 90 possible combinations of "orientation–point–view direction". However, only a part of these combinations could be assumed as representative of the glare conditions occurring within the whole room (step 3). For this reason, the points for which direct sunlight is rarely experienced (points in the rear parts of the room) and the directions of view which do not include a direct view of the window were excluded from the first step of the analysis, but they are still considered in the evaluation of the error committed when applying the $E_{v,thr}$ relative to one point and direction of view to the whole space (Step 2).

3.1 Step 1: E_v thresholds

The $E_{v,thr}$ values identified through the fault-detection analysis by comparing E_v and DGP are shown in Figure 2.

From the analysis of the full dataset some general considerations can be outlined. For each glare comfort class, the $E_{v,thr}$ values tend to grow as the light entering the room increases, that is for higher T_v or lower venetian blind slat angles. Furthermore, for both scattering and specular glazing, the $E_{v,thr}$ values reach a limit value (a plateau) above a certain T_v (which varies depending on the glazing type and glare comfort class). The plateau value is orientation-independent, as the same value is reached both for S and W orientation. Specular and scattering glazing show a different dispersion of the $E_{v,thr}$ values around the plateau, with a higher dispersion for specular glazing and nearly no dispersion for scattering glazing.

As for the lowest $E_{v,thr}$ values, the following considerations can be drawn: for the specular glazing with lower T_v, the lowest $E_{v,thr}$ values are found for +90° and -90° view directions, while for scattering glazing, the lowest $E_{v,thr}$ values is for +45° and -45° view directions. For each view direction, lower $E_{v,thr}$ values are mostly relative to the viewpoints farther from the window (row *b*), and among these, to the side points b0 and b2. Finally, for the windows with VBs and RBs, a common trend cannot be observed.

Figure 3a shows, for each point, the maximum errors committed when the $E_{v,thr}$ are calculated, expressed as percentage of annual occurrences of FP+FN. The maximum errors are lower for the intermediate and upper thresholds (always lower than 16%) and higher for the lower threshold (maximum value equal to 19.74%). Two exceptions to this trend were found with West oriented windows.

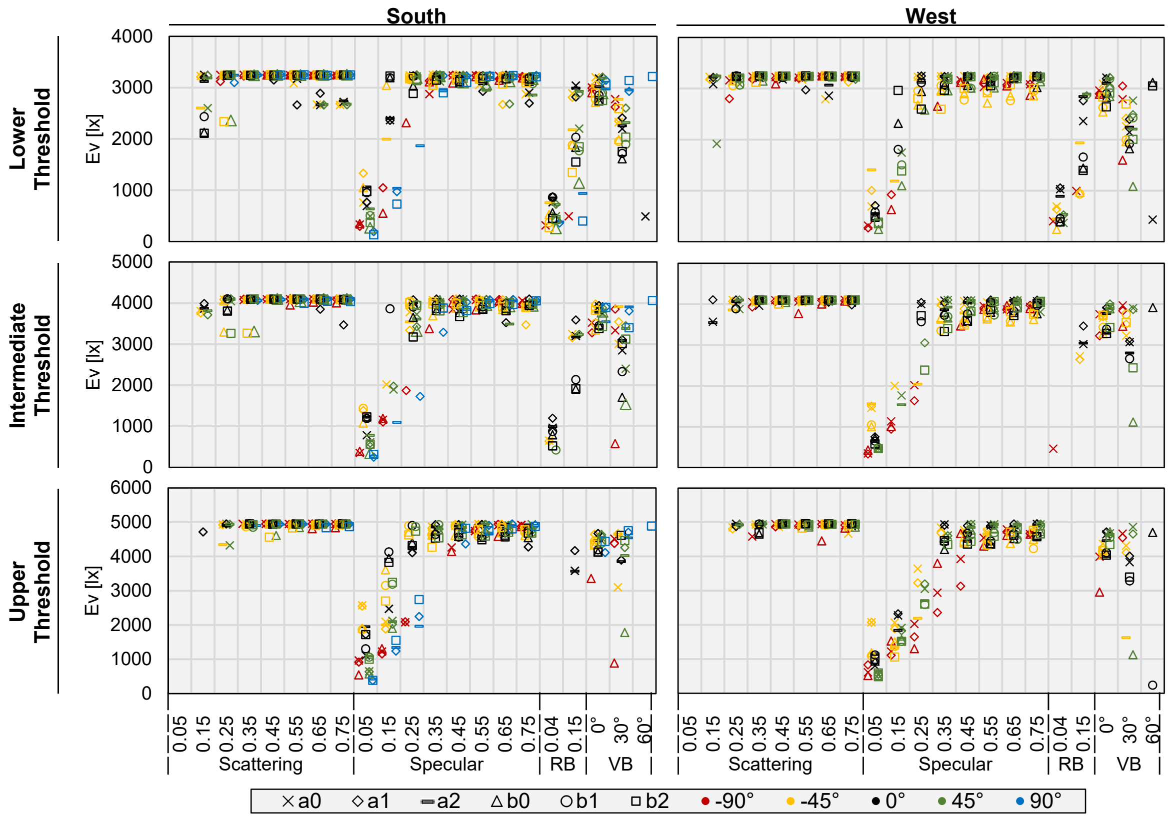

Figure 2 – $E_{v,thr}$ values relative to every window configuration and orientation and to every assumed point and view direction.

3.2 Step 2: errors committed using one point for spatial analysis

The maximum errors committed when applying the $E_{v,thr}$ relative to each point to all the other grid points are shown in Figure 3b, while, Figure 4 visualises the errors relative to all window configurations and directions of view.

Figure 3 – Errors committed (in terms of annual percent FP+FN occurrences): a) calculating $E_{v,thr}$ for each point; b) applying the $E_{v,thr}$ calculated for a point to all the other points.

Most of the maximum errors appear to be lower than 10%, with 5 exceptions: a0, a2 and b2 for the lower threshold in the south orientation, a0 for the lower threshold in the west orientation and b1 for the upper threshold in the west orientation and most likely represent outliers in respect to the average error committed for these points and these thresholds.

The errors committed when applying the $E_{v,thr}$ calculated for each point in the room to all the other points (Figg. 3b and 4) are, with few exceptions, lower for higher daylight glare comfort class thresholds, and higher for the lower class. In addition, errors were found to be lower for scattering than for specular glazing (for both orientations). For the scattering types, lower errors are associated to lower T_v values, and for most cases the errors found are below 2%, while for the specular types, the lower errors are associated to intermediate T_v values, i.e. 0.35 and 0.45. In more detail, as T_v grows from lower to intermediate values, a decrease in errors is observed, while errors increase when T_v moves from intermediate to high. As for the shading devices (VB and RB), it is possible to observe a high dispersion of the errors, which decreases for higher daylight glare comfort class thresholds and which appears to be smaller for the West orientation. Moreover, smaller errors seem to be associated to VB with higher slat angles. However, a common trend for these technologies is difficult to be defined.

From the data presented in figure 4 it is also possible to highlight that the error committed for a specific view direction is quite similar for every considered point. For the S orientation, lower errors are found for +90° and -90° view directions, with the exception of scattering glazing with intermediate T_v (minimum errors for +45° and -45° view directions). The highest errors are found for the 0° view direction, particularly for specular glazing with intermediate-high T_v, while for the other technologies similar errors are observed for the 0°, +45° and -45° view directions For the W orientation, for scattering glazing the lowest errors are obtained for +90° view direction, while for specular glazing lower errors are observed for +90° (lower T_v), 0° (intermediate T_v) and +45° and -45° (higher T_v for the intermediate and upper threshold).

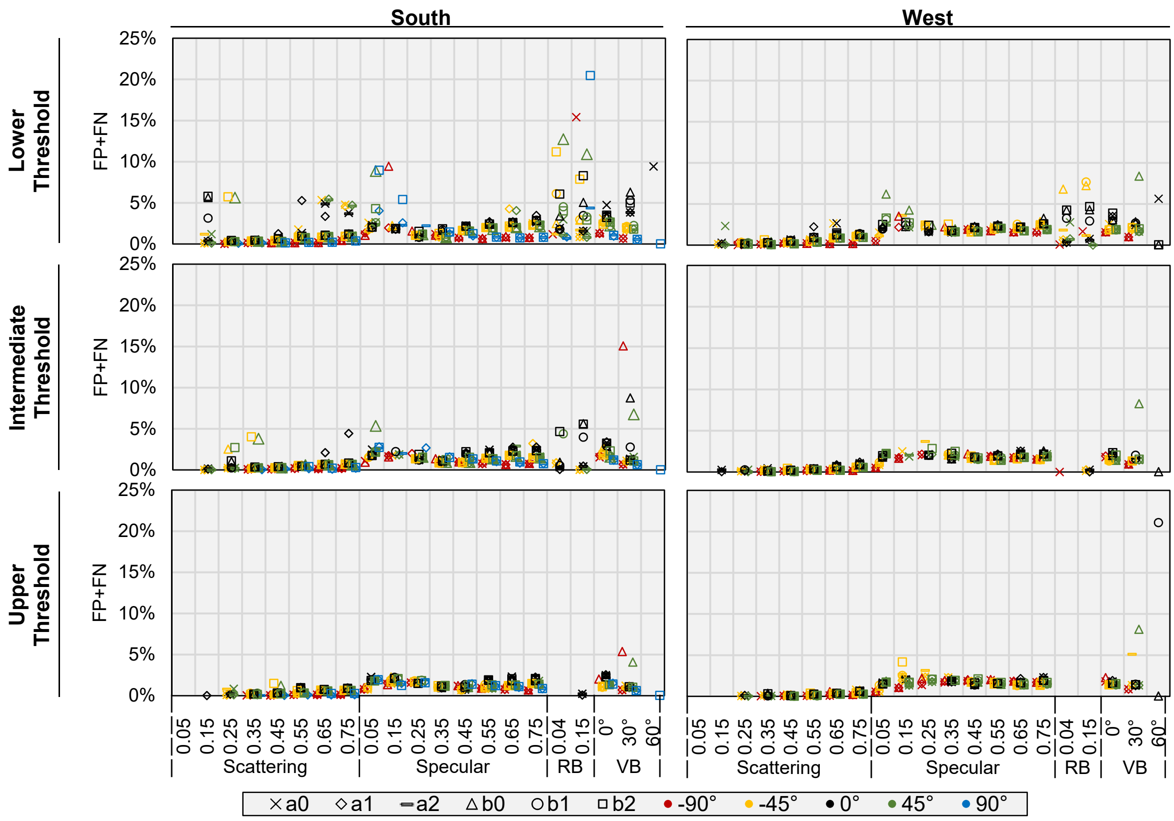

Figure 4 – Errors committed applying the $E_{v,thr}$ calculated for a point to all the other points.

3.3 Step 3: most suitable points for spatial analyses

Figure 5 shows the boxplots and 95° percentile values of the error distributions (expressed as FP+FN) obtained when each point and view direction is used to calculate the glare comfort classes of all other points. It is possible to observe that the error distribution is in most cases not symmetrical, with the first and second quartile comprised in a narrower range than the third and fourth ones. This means that half of the population is comprised in a narrow interval close to 0%, and that for 50% of the time the error committed is very small. Furthermore, many outliers are observed, in particular for points in row *b*. Specifically, points b0 and b2 show several outliers for all the view directions, and in most cases their distance from the median is high. For this reason these two points, for every view direction, are not suitable to assume their $E_{v,thr}$ values to estimate the daylight glare comfort class for the whole space.

The errors corresponding to the 95th percentiles are always lower than 3.5%. This means that a wrong estimation of the daylight glare comfort classes, either FP or FN, occurs more than 3.5% of time only for 5% of the cases considered. The lowest 95th percentiles are obtained for point a0 in the -90° view direction and for point a1 in the -90° and +45° view directions; for these combinations 95th percentiles lower than 2% are observed. Values close, but not lower than 2% are observed for points a0 in the +45° view direction, a1 in the –45° view direction and b1, again for a +45° view direction. The lowest 95th percentile value, equal to 1.86%, was found for point a0 in the -90° view direction.

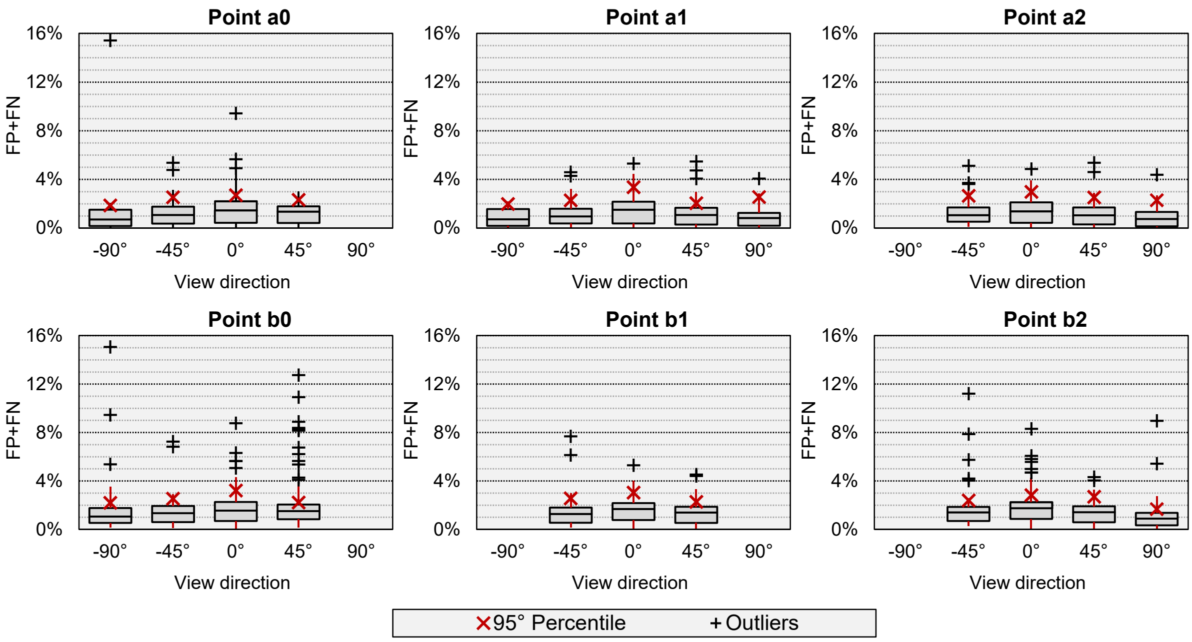

Figure 5 – Boxplots and 95° percentile values relative to the error distributions (expressed as FP+FN), for each viewpoint and direction of view.

However, another aspect should be considered to define the most suitable point for which the only DGP profile should be calculated. As seen, to different points and view directions corresponds a different number of glazing and shading devices for which the calculation of the $E_{v,thr}$ values was possible. A higher number of cases (glazing and shading devices) for which it is possible to calculate $E_{v,thr}$ values results in a higher capability of rating the daylight glare condition of a space. Figure 6 summarises the number of different glazing/shading types for which it was possible to calculate an $E_{v,thr}$ value: it is possible to observe that, for every point, the highest number of cases was found for the 0° view direction, followed by +45° and -45°. Moreover, points in row *a* show a higher number of cases than what found for points in row *b*. Consequently, the highest number of cases for which $E_{v,thr}$ values were calculated is relative to points a0 and a1, both for the 0° view direction.

To conclude, a double approach should be implemented into the design process:

- if the methodology is used for *standard* evaluations, i.e. analyses relative to static glazing with relatively high T_v values, then the most adequate point is the one that minimises the maximum FP+FN error 95th percentile, as the $E_{v,thr}$ values are likely to be calculated for all the points and view directions. This point should be used for the calculation of the annual DGP profile. In this case, this is a0 with a -90° view direction (lowest 95th percentile: 1.86%)
- if the evaluation is relative also to glazing with low T_v values, the combination point-view direction that maximises the number of cases for which the calculation of the $E_{v,thr}$ values is possible should be preferred. In this case the most suitable point/view direction results to be the point a1 with a 0° view direction.

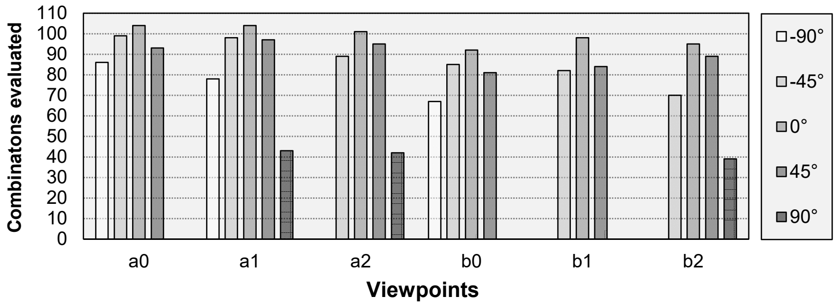

Figure 6 – Number of different glazing types and shading devices for which it was possible to calculate an $E_{v,thr}$ value, relative to all the points and directions of observation considered.

4 Conclusions

The present paper presented a simplified approach to classify a space according to daylight glare comfort classes, by means of vertical illuminances at eye level. The annual DGP is calculated for one point only and is then used as a reference to define the most suitable vertical illuminance threshold values for each daylight glare comfort class for that point. These thresholds are then used for all the other custom-defined points across the room (for which, calculating the annual DGP is not necessary).

This simplified approach proved to be sufficiently accurate for the investigated case study, with a maximum error committed lower than 3.5% for 95% of time for all the analysed cases. The main advantages of this simplified approach are that: (i) a spatial evaluation of the daylight glare comfort classes within a room is possible; (ii) the computation time required for its application is significantly lower than that necessary for calculating the annual DGP for the whole space. The main disadvantage lies in its inability to estimate the exact DGP value, as only the daylight glare comfort class can be estimated for each point. However, this information could be useful enough to support decision making at an early design stage and building operation in a perspective of improving the control of glare conditions for the occupants.

The case study analysed showed a good correlation between the daylight glare comfort classes estimated by means of the approach hereby proposed and those deriving from the DGP evaluation. This is particularly true in the presence of glazing with high T_v, for which the error committed was always below 5%, while for less transparent technologies, i.e. glazing with lower of T_v and shading devices, an error higher than 5% was found in few cases.

The simplified approach was tested on a limited number of cases (i.e. in terms of room geometry and façade options), therefore future work will be aimed at: i) evaluating the accuracy of the approach on larger spaces, different grid resolution, façade options; ii) testing the implication of adopting the presented approach on the design evaluation of alternative façade technologies and on the operations of dynamic facades.

References

Chiaraviglio, L. (2009) Assessment of Discomfort Glare in Daylit Rooms with Shading Devices: Results from a Field Study and Comparison with Software Simulation. Politecnico di Torino, Turin, Italy.

DAYSIM (no date). Available at: https://daysim.ning.com (Accessed: 25 January 2019).

Evalglare (no date). Available at: https://www.radiance-online.org/learning/documentation/manual-pages/pdfs/evalglare.pdf/view (Accessed: 3 December 2018).

Giovannini, L. et al. (2018) 'A simplified approach for the annual and spatial evaluation of the comfort classes of daylight glare using vertical illuminances', Buildings, 8(12). doi: 10.3390/buildings8120171.

Hopkinson, R. G. (1972) 'Glare from daylighting in buildings', Applied Ergonomics. Elsevier, 3(4), pp. 206–215. doi: 10.1016/0003-6870(72)90102-0.

IES Daylight Metrics Committee (2012) 'IES Lighting Measurements (LM) 83-12, Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)'. New York, NY, USA: Illuminating Engineering Society of North America.

Iwata, T. et al. (1992a) 'Experimental study on discomfort glare caused by windows—Part 1: Subjective response to glare from a simulated window', Journal of Architecture, Planning and Environmental Engineering (Transactions of AIJ), 432, pp. 21–33. doi: 10.3130/aijax.432.0_21.

Iwata, T. et al. (1992b) 'Experimental study on discomfort glare caused by windows—Part 2: Subjective response to glare from actual windows', Journal of Architecture, Planning and

Environmental Engineering (Transactions of AIJ), 439, pp. 19–31. doi: 10.3130/aijax.439.0_19.

Mardaljevic, J. (2008) 'Climate-Based Daylight Analysis'. Vienna, Austria: CIE (Commission Internationale de l'Eclairage), pp. 3–26.

Nabil, A. and Mardaljevic, J. (2005) 'Useful daylight illuminance: A new paradigm for assessing daylight in buildings', Lighting Research & Technology, 37(1), pp. 41–59. doi: 10.1191/1365782805li128oa.

Osterhaus, W. K. E. (2005) 'Discomfort glare assessment and prevention for daylight applications in office environments', Solar Energy. Pergamon, 79(2), pp. 140–158. doi: 10.1016/J.SOLENER.2004.11.011.

Radiance (no date). Available at: https://www.radiance-online.org (Accessed: 3 December 2018).

Reinhart, C. F., Mardaljevic, J. and Rogers, Z. (2006) 'Dynamic daylight performance metrics for sustainable building design', Leukos, 3, pp. 7–31.

Velds, M. (1999) Assessment of Lighting Quality in Office Rooms with Daylighting Systems. Delft University of Technology, Delft, The Netherlands.

Waters, C. E., Mistrick, R. G. and Bernecker, C. A. (1995) 'Discomfort Glare from Sources of Nonuniform Luminance', Journal of the Illuminating Engineering Society. Taylor & Francis, 24(2), pp. 73–85. doi: 10.1080/00994480.1995.10748120.

Wienold, J. (2007) 'Dynamic simulation of blind control strategies for visual comfort and energy balance analysis', in 10th International IBPSA (International Building Performance Simulation Association) Conference—Building Simulation. Beijing, China, 3-6 September, pp. 1197–1204.

Wienold, J. (2009) 'Dynamic daylight glare evaluation', in 11th International IBPSA (International Building Performance Simulation Association) Conference—Building Simulation. Glasgow, Scotland, 27-30 July, pp. 944–951.

Wienold, J. and Christoffersen, J. (2006) 'Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras', Energy and Buildings. Elsevier, 38(7), pp. 743–757. doi: 10.1016/J.ENBUILD.2006.03.017.