The Adaptation of Daylight Glare Probability to Dynamic Metrics in a Computational Setting

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Abstract

Because nearly all existing glare equations depend on source size, relative position, and luminance, predicting glare in daylighting software generally requires the pixel-processing of a rendered image meant to reproduce a human's view. When considering multiple positions, views, and times of day and year, making an annual assessment of glare becomes prohibitively time consuming using traditional methods. Using the recently developed metric Daylight Glare Probability as a reference, this paper builds upon an existing approximation method for DGP based on vertical illuminance. The existing method performs well for glare situations based on high vertical illuminance but is less accurate for luminance contrast-based glare. The approach that is presented here suggests a way to overcome these weaknesses by using geometric information and illuminance data generated from the computer model.

Keywords: Daylight, Glare, Visual Comfort, DGP, Climate-Based Performance, Annual Simulation

1. Introduction

In measuring both the quality and quantity of light, there are few factors that are more difficult to quantify, more subjective, and yet more important to visual comfort, than glare. There are at least seven recognized glare indexes: VCP, UGR, BGI, CGI, DGR, DGI, and DGP [1,2,3,4]. These algorithms are complex, unintuitive, do not often agree with each other, and work with unequal accuracy for electric and daylit sources. In addition, glare varies with observer position, view direction, and the adaptability of the eye, so it is no wonder that few lighting design tools offer any glare calculation options. A common early design stage glare control solution is to evaluate it either based on renderings generated -- at most – for one or two viewpoints and a few moments of time, or to not evaluate it at all. As a result, interior blinds are often required after construction. Yet proper control of glare is essential to ensure visual comfort, and most occupants' passive habits – pulling the blinds at the first sign of glare, and then leaving them drawn interminably – can ruin a daylighting strategy. It is therefore imperative that designers be provided with more accessible and intuitive ways to model glare, especially in environments where daylighting is desired. Furthermore, to be most useful, this information should be available as a set of annual, climate-based glare data, pertinent to an area of space, not just a single position. This poses a challenge, as glare is highly dependent on an occupant's position and view direction and defined for in a single moment in time.

Recent work in daylighting metrics has been moving more towards annual, climate-based analyses, either by condensing the temporal data and displaying it on spatial graphs, such as Daylight Autonomy (DA) or Useful Daylight Illuminance (UDI) [5,6], or by condensing spatial data and displaying it on temporal maps [7,8], or both [9,10]. Some annual performance research specific to glare has been done by Wienold, who produced Daylight Glare Probability (DGP) values using a modified version of the program Daysim [11,5]. Because traditional glare evaluations from pixel analysis are computationally intensive, this effort was furthered by the development of an illuminance-based linear approximation for DGP (see Section 2) which, while it made the annual calculation possible, has some limitations in high-contrast glare situations.

In early-stage architectural design, temporal graphics can help determine if and when lighting design goals have been met. A previous study done by the authors concerned the condensing of spatial illuminance data to a single point so that it can be displayed on a temporal map [8]. In that case, the color of each point on the map represents the percentages of a sensor plane which meet, overstep, or remain below some user-defined illuminance goals (see Figure 1). The same principal could be applicable to the portion of a space in which one perceives glare, but to be realistically applied, the methods for computing glare must be made more efficient. High-speed annual glare evaluations would be a valuable tool, and there may be enough information in the computer models themselves to create a viable approximation method for all scenarios. This paper builds on the DGP equation and uses model geometry and illuminance data make the existing DGP approximation more flexible.

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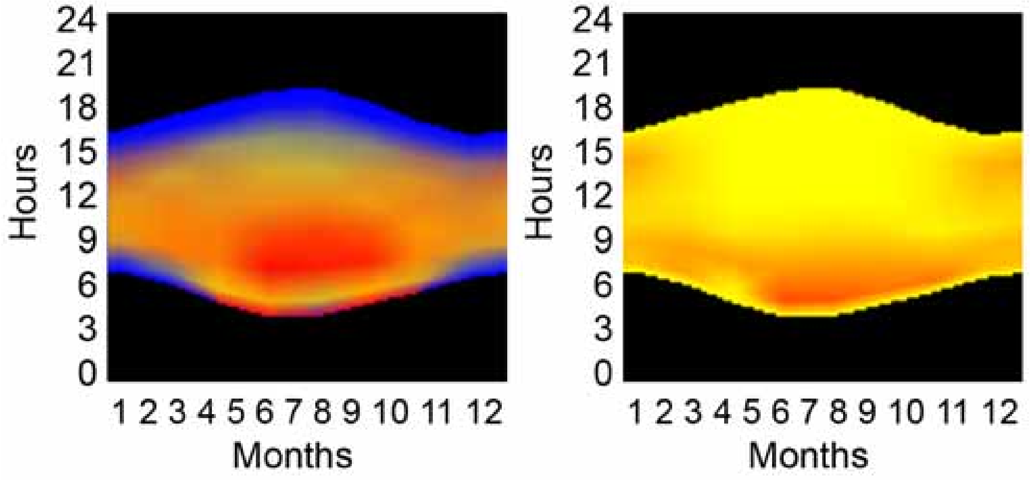

Figure 1. The temporal map on the left represents the percent of a sensor plane which has met (yellow), overstepped (red), or not reached (blue) a user's illuminance goals. The temporal map on the right represents the percent of a vertical sensor array which perceives glare (red) or no glare (yellow).

2. Daylight Glare Probability

The earliest glare metrics were not intended for the variable, diffuse area sources common to daylighting, but several advances have since been made. One of the most promising new metrics for daylighting is Daylight Glare Probability (DGP), developed by Wienold and Christoffersen [4], which represents "percent of people disturbed" and is based on human reactions to daylight-based glare in a side-lit office environment with venetian blinds. Like most glare calculations, finding DGP requires the size, position, and luminance of the source, as shown in the equation below:

$$DGP = 5.87 \times 10^{-5} E_v + 9.18 \times 10^{-2} \log\left(1 + \sum_j \frac{L_{s,j}^2 \omega_{s.j}}{E_v^{1.87} P_j^2}\right) + 0.16 \tag{1}$$

where E_v is the vertical illuminance at the eye, L_s is the luminance of the glare source, ω_s is the solid angle of the source, and P is the position index of the source. The variable values are usually found by pixel-processing an HDR photograph, rendering, or CCD image. For predictive computer models, this process is prohibitively time consuming when considering multiple positions, viewpoints, and times of day and year, making it difficult to predict the glare potential of a whole space on an annual basis. One solution would be to find a way to reliably predict glare by performing illuminance calculations only, which take much less time to compute.

Since DGP is heavily influenced by the vertical illuminance component, it can be approximated in some instances by using a linear equation based solely on that variable. This linear equation, as defined by Wienold:

$$DGPs = 6.22 \times 10^{-5} E_v + 0.184 \tag{2}$$

demonstrated a remarkable correlation with DGP for instances when E_v is composed only of indirect light [11]. This is no great weakness, however, since many daylight simulation programs can distinguish indirect from direct light, and it is reasonable to assume that there will be a glare issue whenever direct light hits the eye.

As Wienold recognized [4], the aspect of glare not addressed in this equation is that of luminance contrast. The data set from which equation (2) was derived was based on a two-person office model where a large window took up much of the view. In that scenario, glare caused by luminance contrast would not be nearly as common as glare caused by high luminance levels, so disregarding the logarithm term, which is the contrast component of the glare equation, is not a problem. On the assumption that other models would require the contrast component to accurately predict DGP, however, an approximation method which includes that aspect of the equation (1) would be an asset.

3. Approximation Methodology

The variables that must be found to complete the full DGP equation (1) are the luminance of each glare source (L_s), the solid angle of each source (ω_s), and the position of each source (P). The sources must also be identified and defined, a task which can be a challenge even for traditional daylight glare analysis. On the other hand, if one is working inside a daylight modelling program, there are certain inherent advantages. First and foremost, the program already has a definition of the model's geometry. The sensor position and view direction is known, and if the sources of glare could be attached to physical objects in the model, the solid angle ω_s and position index P, which are merely geometric quantities, would be easy to find. The main problems, therefore, are to find glare sources, attach them to a physical object, and approximate the luminances.

When inside a building, the most common sources of glare are direct or indirect light from the exterior, specular reflections, and electric light fixtures. Because the authors are working on daylighting analysis with the LSV radiosity-based rendering engine that does not yet include specular material definitions [12], this paper will focus on windows as the probable source of glare. However, since electric lights and specular materials must have a defined directional exitance, one may presume that a similar methodology could be applied to them. The LSV radiosity program takes a triangular-meshed object file which divides all surfaces into similarly sized patches with assigned material definitions.

The first assumption, therefore, is that any window patch is a possible glare source when viewed from the interior. We can sort through them by assigning an approximate luminance to each patch and an approximate adaptation luminance to each view position and direction, represented by a vertical illuminance sensor. A constant luminance integrated over a hemisphere, weighted by the cosine to the normal, is related to illuminance by a factor of π, so we will take E_v/π as a working value for adaptation luminance: our second assumption. For our third assumption, we should recall that our rendering program has sky luminance distribution data as well as geometric data. By creating a line of sight between the sensor and the window patch and applying the known sky illuminance distributions, we can figure out the luminance of the sky as seen through that window patch. Because the validation for this paper was done using Radiance simulations (see Section 4), the sky distributions were copied from the C code of *gensky*.

A threshold luminance of four times the adaptation luminance was set to keep lower-illuminance glass patches from being considered glare sources (this is the default setting in the program *evalglare* – see Section 4), and if the vector between the eye and any glass patch is below the horizontal, it is eliminated on the assumption that the view through the window will be of the ground. Finally, since DGPs is only valid for indirect light, the simulations were done under the CIE clear, clear-turbid, intermediate, and overcast sky models, rendered without sun to make all data points viable for comparison. Full-sun simulations for the model-based-method are not shown here, but the errors were similar to that of the no-sun simulations.

One potential weakness of this method is that larger window glare sources will get interpreted as several smaller sources. This could make the approximation tend to overestimate DGP. Another potential weakness is considering the ground a non-glare source, whereas it might contribute to the perception of glare if seen in high contrast through the window.

4. Simulation

For each model, point, and view direction, a picture was rendered with Radiance, and DGP was measured using the program *evalglare* [4]. The illuminance at each point and at the glass patch positions was either taken from an identical calculation of point illuminance or from the detailed *evalglare* output files.

Because the goal is to use this method with the LSV radiosity-based engine mentioned in the last section (both this method and the LSV are being developed in the framework of the Lightsolve project described in [7]), the geometry of each model tested is in the form of a triangular-meshed object file. However, all simulations of illuminance or DGP were done using an identical Radiance model with interior and glass sensor points derived from the object file. The reasons for this are that the *evalglare* program works with the Radiance software, which is a validated and trusted simulation program. Data from four models will be presented here: "Classroom", "Skylights", "Frame", and "Simple Corbusier". The Classroom model is a rectangular room located in Sydney, Australia, with two big punched windows to the south, six smaller punched windows to the north, and an external overhang over the lower three windows to the north. The Skylights model is the same size, shape, and location as the Classroom model, but it has no punched windows and two large skylights. The Simple Corbusier model is again the same size and shape as the previous two, but it has many scattered small windows on the south and east and a tall window to the northwest. It was inspired by the Chapel of Notre Dame du Haut by Le Corbusier, but the simulation location is Boston. The Frame model is a slightly smaller rectangular room located in Boston. It has one large window divided into pieces with a thick dark window frame and facing 20 degrees south of east. Classroom and Skylights were analyzed in the initial set of explorations in which nine view positions with eight view directions each were simulated. In subsequent model simulations, for the sake of time, only a few view points and view directions were chosen. Sample renderings of each model can be found in Figure 2, and their dimensions, reflectances, and Radiance parameters are listed in Table 1.

Several other models were also made in an attempt to simulate glare due more to contrast than illuminance levels, including a detailed model of Ando's Church of Light in Osaka, Japan, and a very simplified model inspired by Safdie's Yad Vashem museum in Jerusalem, Israel. However, DGP is not valid for low illuminances [11], and it is difficult to find contrast-based glare situations at higher illuminances. Both the DGPs approximation and the method described above seemed to fail for these other models (the former by underestimation, the latter by overestimation), but the since the DGP itself is invalid, the results are inconclusive.

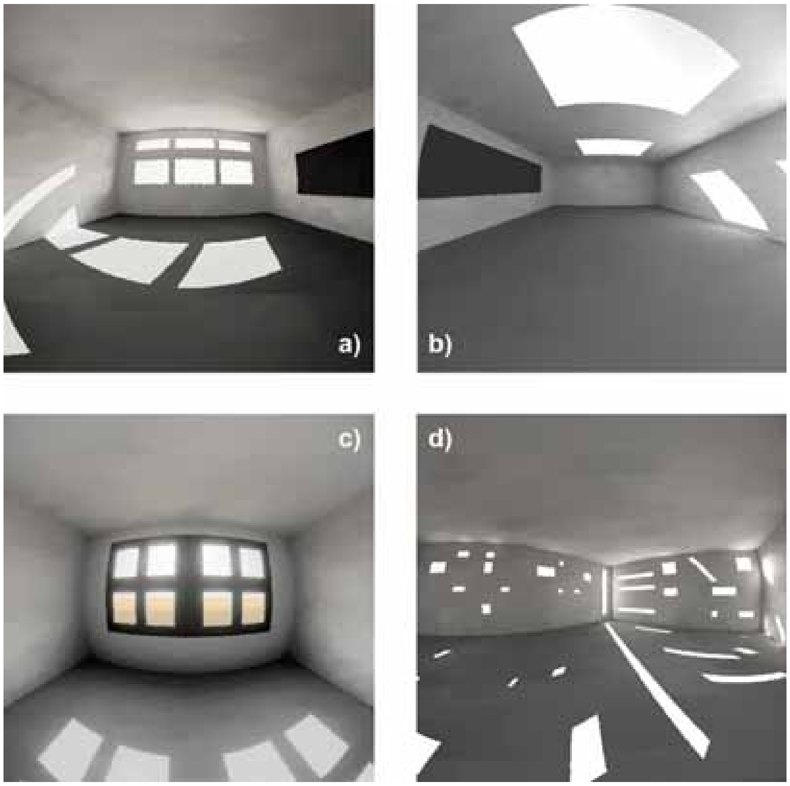

Figure 2. Rendered interior views of the models. a) Classroom, b) Skylights, c) Frame, and d) Simple Corbusier.

5. Results and Discussion

Results for both approximation methods are given in the form of percent error from the corresponding pixel-analysis DGP. Both scatter plots and histograms are provided for each model in figures 3 and 4.

The Classroom model is the one closest to the data on which equation (2) is based, in the sense that is has large areas of vertical windows and the glare situations are mostly illuminance-based, rather than contrast-based. Unsurprisingly, figure 3 shows that this existing DGP approximation (DGPs method) performs very well in the Classroom model, with most errors occurring between -10% and 0%. Fortunately, the model-based approximation performs similarly well, with most errors occurring

Table 1. Geometric and simulation parameters of the three models.

Model	Classroom	Skylights	Frame	Simple Corbusier
Dimensions (m)	7.5 x 10 x (3 to 4)	7.5 x 10 x 3	5 x 7 x 3	7.5 x 10 x 3
Wall Reflectance	0.65	0.65	0.5	0.5
Ceiling Reflectance	0.83	0.83	0.5	0.65
Floor Reflectance	0.2	0.2	0.2	0.2
Chalboard Reflectance	0.05	0.05	n/a	n/a
Frame Reflectance	n/a	n/a	0.15	n/a
Glass Transmisivity	0.8	0.8	0.8	0.8
# Sensor Points	9	9	1	1
# Views per Sensor	8	8	1	3
Radiance Parameters:				
ab	5	5	5	5
ad	512	512	512	512
ar	128	128	128	128
as	128	128	128	128
dp	512	512	512	512

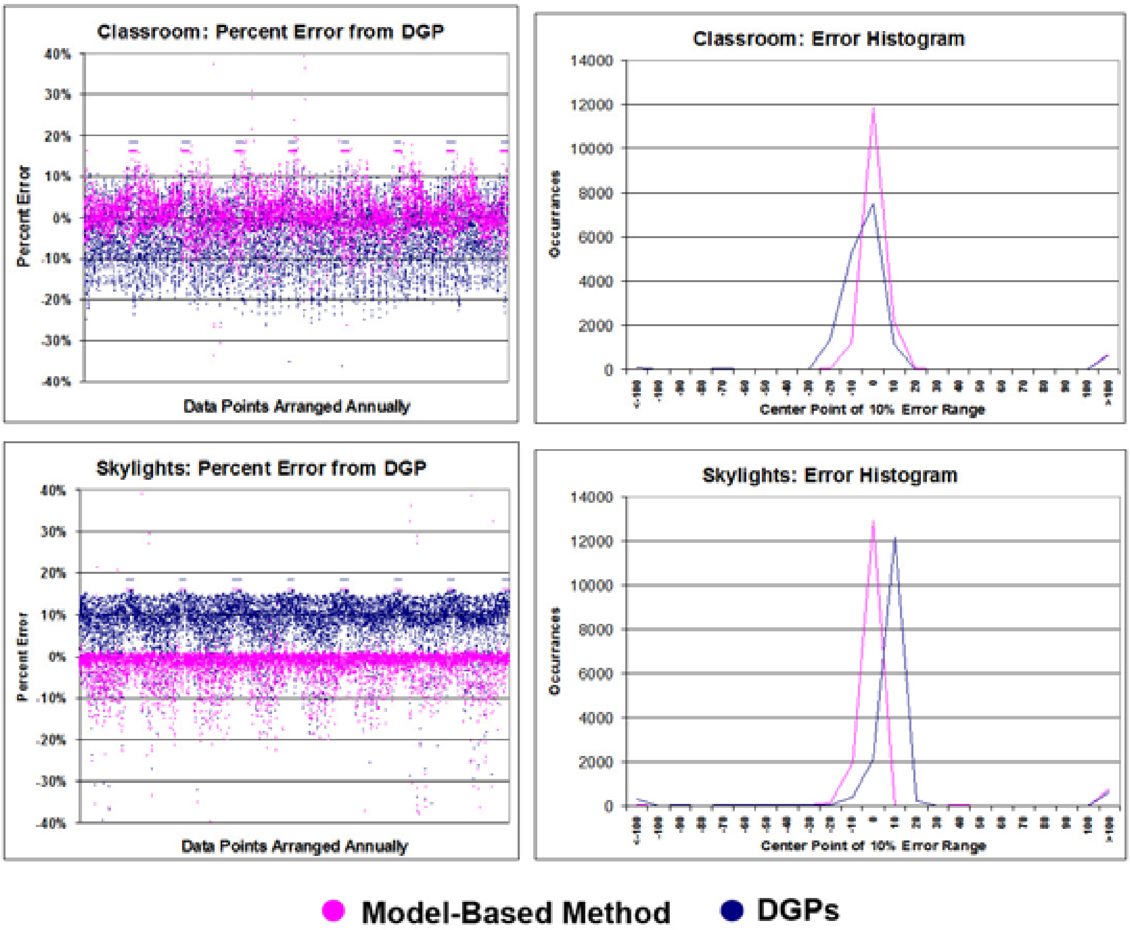

Figure 3. Error data for both approximation methods, Classroom and Skylights models. The scatter plot points are dislpayed annually from left to right (7 times of day on 8 days of the year).

between -5% and +10%. In most vertical-window cases, this is typical of each approximation method; DGPs has a tendency to underestimate, and the model-based approximation tends to overestimate glare. In the sense that glare is something one wishes to avoid, this makes the latter the more conservative method when the relative errors are the same.

The Skylights model is the only one shown in which the DGPs approximation overestimates the actual DGP. (Similar results occurred in another skylight-dominated model which was not included due to many data points being below the valid range for the DGP equation.) As shown in figure 3, DGPs hovers largely around +10% error, while the model-based approximation ranges between -10% and 0%, with many points near 0% error. One possible reason for the unusual overestimation on the part of the DGPs approximation might be that, while illuminances in the room remain high due to the large skylights, the possible glare sources are mostly at the very edges of the visual range, which means they have a smaller impact on the eye.

The Frame and Simple Corbusier models (see figure 4) were attempts to create contrast-glare situations (with a high enough illuminances such that the DGP itself is still valid). The Frame model is the only one for which the model-based method systematically underestimates the DGP – although it still gives closer results than the DGPs method. Further investigation revealed that *evalglare* considered every window pane a glare source, while the model-based method considered only those panes looking at the sky to be glare sources. This is one example where the ground is actually a glare source even though it was disregarded in the approximation (see Section 3).

For both models in figure 4, the DGPs approximation constantly underestimates glare probability by around 20% for all sky types. Both models are lower-illuminance in general, with higher contrast points such as a bright glass pane against a very dark frame or small windows scattered over the visual field. Since DGPs is dependent entirely on vertical illuminance, it misses the instances of

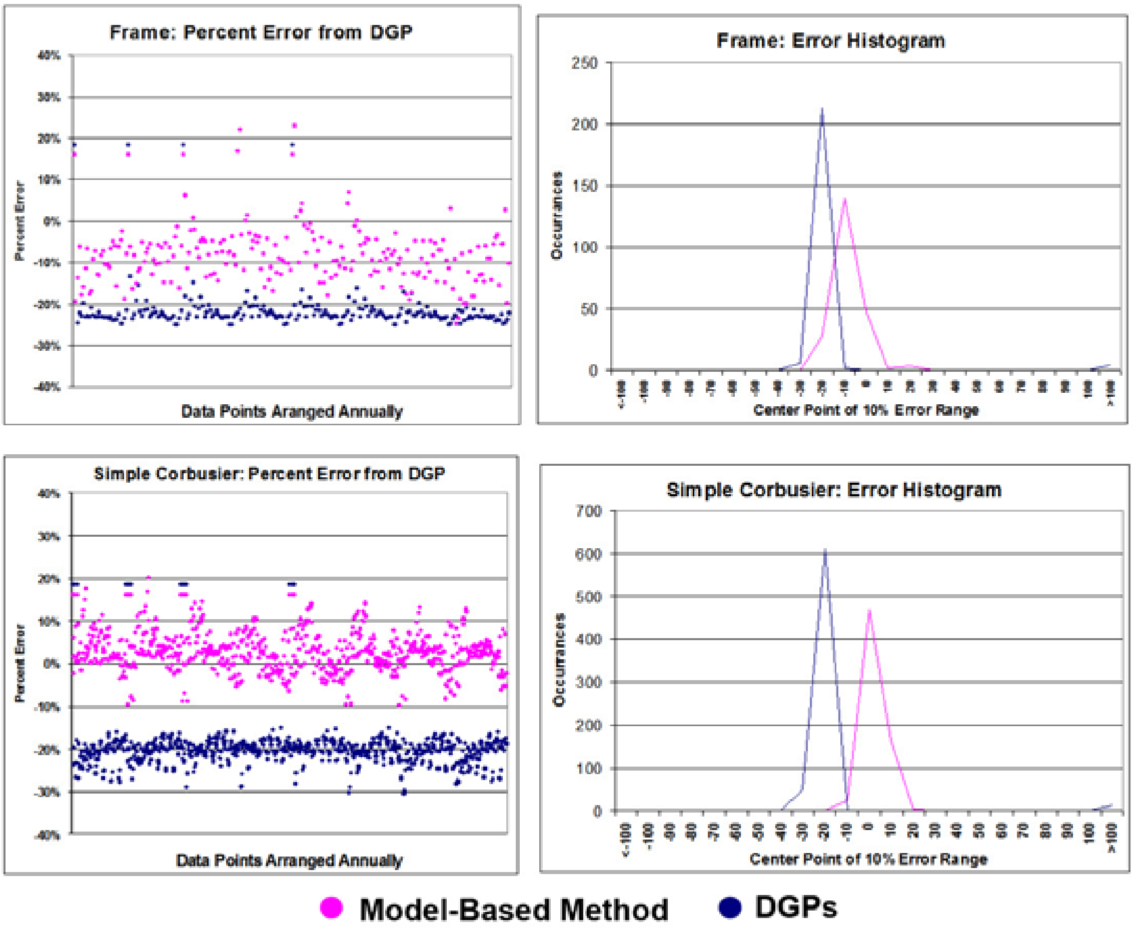

Figure 4. Error data for both approximation types, Frame and Simple Corbusier models. The scatter plot points are dislpayed annually from left to right (7 times of day on 8 days of the year).

contrast-based glare. For the model-based approximation, the results for Frame stay mostly between -10% and 0% error, and those for Simple Corbusier range between 0% and +10%.

In general, the model-based method is potentially valid for more scenarios than DGPs because it allows for the approximation of contrast-based glare and non-vertical windows. Furthermore, the Classroom model showed that it could also be very accurate for glare caused mainly by high luminances through vertical windows. The model-based method also avoids overestimating the glare from skylights which, while bright, are at the edge of the visual field. Finally, the model-based method's tendency towards more positive error (except in circumstances where glare sources are disregarded, such as the Frame model) makes it a more conservative method than the DGPs, which tends to underestimate the DGP.

6. Conclusions

The results show that, while DGPs is a great approximation method for high luminance glare, it does not adequately represent contrast-based glare. It performs very well in the Classroom model, which has large vertical windows and glare caused mostly by the quantity of light hitting the eye. In the Skylights model, it overestimated the glare a little, probably due to the bright space combined with the position of the glare sources. In the Frame model and the Simple Corbusier model, the DGPs approximation underestimated the DGP to nearly the greatest extent allowed by the DGPs equation. This is likely due to the lower-illuminance situations in which glare was largely due to luminance contrast.

Conversely, the model-based method performs within 10% of the DGP nearly all the time, and within 5% of the DGP most of the time. The only model in which this is not true is the Frame model, where the error is centered around -10%, although this is likely due to the fact that *evalglare* considered the ground a glare source and the model-based method did not.

Every model shown in this paper was generally rectangular in nature. To use this method for any situation in which the view of the sky or the window may be masked from the sensor point, such as in "L" or "E" shaped buildings, the rendering engine would need to indicate that the line of sight to the sky is blocked. While this is not yet implemented in the LSV engine, the authors will look into adding it in the near future. It is possible that the luminance of diffuse external materials could be simultaneously determined, so that bright exterior objects are not immediately disregarded as glare sources. Also, though it has not been rigorously tested, full-sun data indicates that the model-based method works for more than just no-sun data. However, it is also reasonable to assume that if there is direct sun on the vertical sensor, there is a corresponding perception of glare.

The real test of the model-based approximation method would be very low illuminance situations with high luminance contrasts. These scenarios are common in religious architecture and in rooms with lower-reflectance walls (such as dark wood panelling) and can't be ignored. An approximation method which is fast and reasonably accurate for all scenarios could make glare data available for analysis on an annual scale – and give architects a better chance to make informed decisions about daylighting design.

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