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DYNAMIC DAYLIGHT GLARE EVALUATION

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ABSTRACT

In non-residential buildings, comfort and energy demand for heating, cooling and lighting are significantly influenced by the façade.

Up to now, only non-weighted luminance-based methods for calculating and evaluating annual daylight glare exist (Lee et al., 2005; Mardaljevic and Lomas., 1998). Within this paper, different methods based on the daylight glare probability DGP (Wienold and Christoffersen, 2006) for a dynamic calculation of glare are discussed and evaluated:

1. Timestep by timestep calculation – RADIANCE reference method.
2. Simplified daylight glare probability DGPs – DGP only based on vertical eye illuminance. Results of this method are similar to average luminance based evaluations.
3. Enhanced simplified DGP calculation - DGP based on vertical eye illuminance and simplified images.

The enhanced simplified DGP method is validated against two hour-by-hour full year calculations, using a fabric and a Venetian blinds shading system.

For the yearly evaluation of dynamic glare results, a histogram analysis and a glare rating classification is proposed.

INTRODUCTION

The behaviour of the building's façade follows ambient weather conditions and seasonal differences dynamically. Many façade constructions also have a strong dependency on the angle of incidence – especially regarding transmittance. In addition to this, movable shading devices like Venetian blinds are often used in Mid-European countries to enable user interaction, glare protection, view contact and to protect the building from solar loads during summer.

For an overall glare assessment of façades and/or comfort in an office space it is therefore necessary to evaluate the behaviour throughout a year and not only statically for selected situations. Existing annual glare evaluation methods are based on average luminance values within the field of view (Lee et al., 2005) or on the fraction of occurrence of high luminance values within the field of view (Mardaljevic and Lomas., 1998). The average luminance method is similar to the investigated DGPs method. The second method is promising but should be approved by user assessments and is not investigated further within this paper.

SIMULATION METHOD

The presented method is based on the RADIANCE (Ward and Shakespeare, 1998) simulation environment as well as on the DGP and user assessments (Wienold and Christoffersen, 2006). RADIANCE uses a backward raytracer and is capable of simulating specular (glossy) materials. This is very important for the correct calculation of the light transport through blinds and also for glare prediction. Of course, time-series simulations are of interest for the investigation of the annual behaviour. To generate those time series (hourly time steps or shorter) the RADIANCE-DAYSIM tool is used. DAYSIM uses the daylight coefficient method and is described in (Reinhart and Walkenhorst, 2001). For a given office geometry, orientation and location, all possible shading positions are simulated for all time steps using the respective climate data.

For the glare evaluation, the evalglare tool (Wienold, 2004) is used. Evalglare is based on user assessments and calculates the probability, that a person is disturbed by glare. This so called DGP (daylight glare probability) was introduced in (Wienold and Christoffersen, 2005) and has been validated (Wienold, 2009; Wienold and Christoffersen, 2006).

MODEL SET UP

For the dynamic glare investigation, an exemplary model of the test rooms at Fraunhofer ISE, Freiburg (Germany) is used. Two different façade types are modelled:

1. Band façade
2. Fully glazed façade with parapet

The dimensions of the models are:

Office depth:	4.61 m
Office width:	3.62 m
Office height:	2.85 m
Glazing area (band façade):	4.28 m²
Glazing area (fully glazed façade):	6.63 m²

The office has, in principle, two workplaces. For this study, however, only the front workplace is used (distance to façade is 1.3 m for the illuminance measurement at 0.8 m height, and 1.6 m for the view position for the glare evaluation at 1.2 m height respectively).

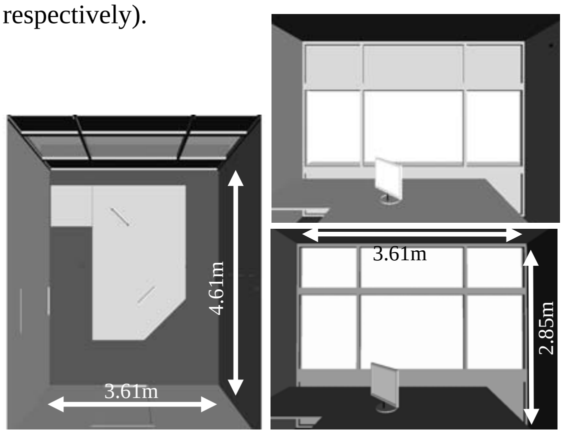

Figure 1: Layout of the office model. Left: Top view. Right: View towards the fully glazed façade with parapet (0.9 m height, upper image) and the band façade (lower image).

The following main material property values are used for the simulations:

Wall, door and frame reflection factor:	0.5
Ceiling reflection factor:	0.8
Floor reflection factor:	0.2
Glazing visual transmission:	0.75

Shading models for the example office

For this study, an unshaded office and two different shading systems are simulated. The material values are taken from spectral measurements of the blinds. The simulation variants within this developing simulation phase are:

1. Unshaded: The office is unshaded throughout the year. The room geometry is used in combination with the fully glazed façade with parapet.
2. Fabric roller blind: Type: Ferrari Textiles, Soltis SK20, grey-alu 2116E
   Total transmission: τ_{vis}=0.04,
   Direct transmission: τ_{Dvis}=0.01,
   Total reflection ρ_{vis}=0.42.
   This interior system shades the window completely. The roller blinds are only used in combination with the fully glazed façade with parapet.
3. Venetian blinds: These 80 mm blinds are curved, the distance between the slats is 72 mm. The color is diffuse silver with a reflection factor of ρ_{vis}=0.52. The surface shows some glossy properties (specular reflection 5%). The blinds are mounted externally in front of the façade. They are lowered completely and the slat angle is 15° (horizontal position is 0°). The Venetian blinds are only used in combination with the band façade.

Weather data set and sky model

A weather data set of Brussels based on hourly values is used for these simulations. The dataset is generated by (Meteonorm, 1999). For all simulations, the Perez all weather sky model is used (Perez et al., 1993).

Rendering parameters

Within this study, following rendering parameters for RADIANCE are used. These settings seem to deliver reliable values for the given scenes and shadings – but are not intended to be a general setting for the calculation of offices. For the purpose of comparison, the same settings are used for all methods described – except the –ab value for the DGP calculation using the enhanced simplified method.

The settings are:

Ambient bounces (-ab):	7
Ambient divisions (-ad):	2048
Ambient supersamples (-as):	512
Ambient resolution (-ar):	256
Ambient accuracy (-aa):	0.13
Limit reflections (-lr):	6
Specular threshold (-st):	0.02
Specular jitter (-sj):	1.0
Direct jitter (-dj):	0.00
Direct sampling (-ds):	0.2
Direct pretest density (-dp):	512

TIMESTEP BY TIMESTEP CALCULATION – RADIANCE REFERENCE METHOD

For every hour with available daylight of the year, a full 180° image (size: 300x300 pixels) is calculated by common RADIANCE rendering routines (using rpict). Afterwards, all calculated images are evaluated by evalglare.

This method is - using the simulation parameters mentioned before - very time consuming and is in this context only used as a reference method. One of the main reasons for the long computation time is the interreflection calculation within the scene (-ab parameter).
Currently (in the year 2008), on an AMD Opteron processor using 2.6 GHz the rendering time for an image using the upper mentioned parameters is about 50 min to 2 hrs. For a typical weather data set 4100-4500 hrs of daylight are available (e.g. for Brussels 4348 h) – the resulting rendering time is more than half a year on a single processor machine. Assuming a power increase of CPU by factor two in two years (Intel, 2005) the calculation time would be 120-300h in 10 years from now .

Of course, the computation time is strongly depending on simulation parameters and the simulation times mentioned above are only valid for the used simulation parameters. It would be favourable to invent a parametric study to see the influence on the glare results – but this is beyond the scope of this paper. However, the computation time shown above underlines the need for faster methods.

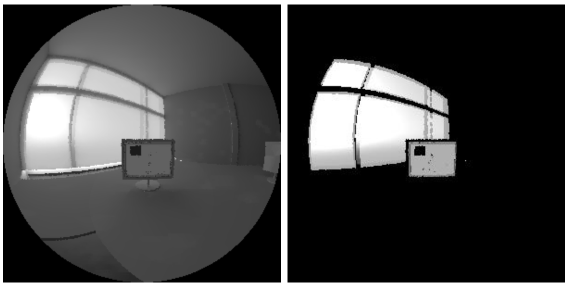

Figure 2: Left: Example of an hour-by-hour RADIANCE generated image (reference method). The image shows the fabric shading type for the fully glazed façade scattering the sun and sky. Right: Example of a simplified image (-ab 0) for the same façade setting.

SIMPLIFIED DGP

To overcome the great effort required to generate images at every time step of the simulations, a simplified method to calculate the DPG is investigated. In (Wienold and Christoffersen, 2006), it is shown that the vertical illuminance at eye level shows a reasonable correlation to the glare perception. From this, a simplified DPG (named now DGPs) could be derived as:

$$DGPs = 6.22 \cdot 10^{-5} \cdot E_v + 0.184 \qquad (1)$$

This equation neglects the influence of individual glare sources. Therefore the DGPs can be applied only if no direct sun or specular reflection of it hits the eye of the observer (Wienold, 2007).

Since the DGPs is based on the vertical eye illuminance only, the value can easily be calculated by DAYSIM, using a single calculation point only.

ENHANCED SIMPLIFIED DGP CALCULATION

The major shortcoming of the simplified DGPs is that it neglects the influence of peak glare sources. In fact, for the evaluation of façades and shadings, which are cutting the view contact to the sun, the simplified DGP seems to be suitable. However, as soon as the façade also shows a direct transmission component or a peak scattering in sun ray direction – another, more reliable evaluation method is necessary.

The idea of this method is based on the fact that the DGP consists of two terms in its formula. One term (term 1 of eqation 2) depends on the vertical eye illuminance and the other term (term 2 of eqation 2) on the detected glare sources (size, luminance and position). The vertical eye illuminance can easily be calculated by DAYSIM. However, the second term needs a image evaluation.

$$DGP = \underbrace{c_1 \cdot E_v}_{\text{Term 1}} + \underbrace{c_2 \cdot \log(1 + \sum_i \frac{L_{s,i}^2 \cdot \omega_{s,i}}{E_v^{c_4} \cdot P_i^2})}_{\text{Term 2}} + c_3 \qquad (2)$$

The idea is to calculate a simplified image, which includes the main glare sources, without spending too much effort in calculating the exact luminance distribution within the room. Using such a simplified image for the evaluation with evalglare implies the provision of the correct vertical illuminance. This vertical illumiance value can be calculated by DAYSIM in advance.

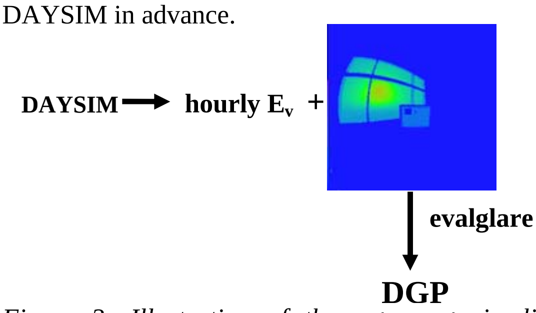

Figure 3: Illustration of the enhanced simplified method for the calculation of the DGP

RENDERING PARAMETERS FOR THE SIMPLIFIED IMAGE

Compared to the hour-by-hour simulations, the rendering of a image must be fastened up tremendously. At the same time the accuracy of rendering the glare sources must be kept. The accuracy can be low for the entire light distribution including the indirect lighting by interreflections. To achieve this rendering time reduction, the calculated interreflections must be reduced or left out completely.

The highest time reduction can be achieved when leaving out the indirect reflections completely – which means leaving out the so-called "ambient calculation" within RADIANCE (using –ab 0). For non-scattering façade materials (like glazing, Venetian blinds) this leads to reliable results (see paragraph *Comparison and validation*).

For scattering materials like fabrics, the choice of the rendering parameters is more complicated. Without the ambient calculation, all light coming from the sky (not the sun) will not be considered within the simulation. Therefore, the luminance of the façade is much lower than in reality. Anyhow, high peaks caused by the sun will be considered and, as the vertical eye illuminance takes the correct luminance of the façade integrally into account, this restriction might be of minor influence in many cases. The described effect appears only for scattering materials – sky contribution of "conventional" glazing is also calculated without ambient calculation.

In the following figures, the influence of different -ab values on the façade luminance is shown. The effect of the dynamic DGP is evaluated in the *Comparison and validation* paragraph. In conclusion switching off the ambient calculation for the simplified image calculation leads to reasonable results in most cases. When applying the method to a scattering façade without doing pre-tests, an –ab value of 1 is recommended to be on the safe side.

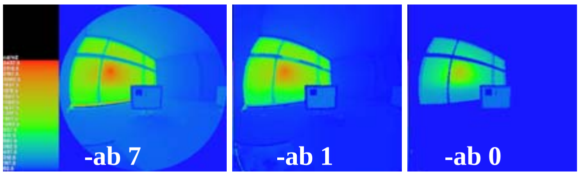

Figure 4: Influence of different –ab rendering parameters on façade luminance for the fabric material. Using –ab 0 results in too low luminance values in the façade area (~50% of the reference value using –ab 7). Using –ab 1 results in reasonable façade luminance values (~10% difference to the reference).

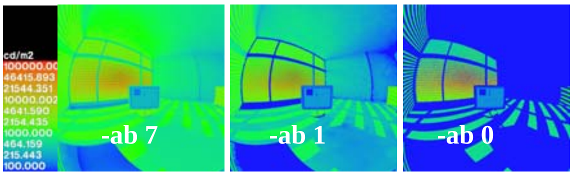

Figure 5: Influence of different –ab rendering parameters on façade luminance for the Venetian blinds. The part of the radiation falling directly through the blinds is more or less similar for all variants. The main differences between the variants is the luminance on the blinds. Depending on the reflectance factor, this might also be an issue for the glare source detection.

COMPARISON AND VALIDATION

For the calculation of the DGP via the enhanced simplified method, several errors can occur when compared to the reference hour-by-hour method. First of all, the calculation of the vertical illuminance by DAYSIM potentially generates an error. This illuminance value is used by the simplified and the enhanced simplified method. In this context, the major DAYSIM error is caused by the discretisation of sun position distribution. For the used DAYSIM version (2.1 for Linux), 60 sun positions are calculated within the simulations. The interpolation between them leads to an error, which could be decreased by increasing the number of sun position in future DAYSIM versions. Besides these deviations caused by DAYSIM, other deviations to the reference method could be provoked by using the –ab option of RADIANCE or by simplified methods themselves. Furthermore, small deviations could occur by different detection parameters using evalglare – especially for low light levels.

Therefore, it is essential for the validation to split up deviations into

- deviations caused by the DAYSIM sun distribution method.
- deviations caused by the –ab 0 option.
- deviations caused by the simplified method itself.

For that reason, two input data sets are used for the simplified methods:

1. To judge the method itself without the DAYSIM error, an input data file is generated using the vertical illuminance calculated by the hour-by-hour-method.
2. An input data set is generated using the vertical illuminance calculated by DAYSIM.

All enhanced simplified calculations are done with –ab 0 and –ab 1 in order to see the influence of this simulation parameter.

For the fabric material the two simplified methods are compared to the reference method using the hour-by-hour illuminance values as input (figure 6). For that case, the results of the enhanced methods correspond better to the reference values than the pure simplified method (DGPs). Using –ab 1 instead of –ab 0 shows no large improvement. Using the DAYSIM calculated input data shows slightly higher DGP values compared to the reference method.

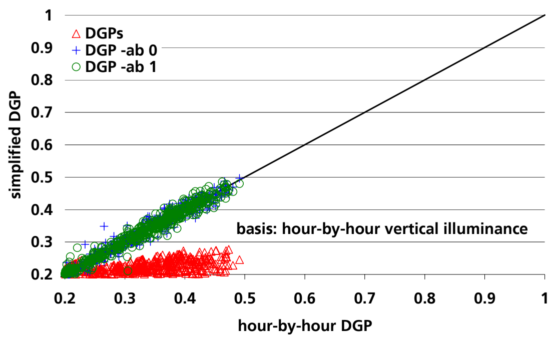

Figure 6: Fabric shading: Comparison of the DGP-values of the simplified methods (y-axis) with the reference method (hour-by-hour calculation, x-axis). The simplified method uses hour-by-hour calculated illuminance values in order to illustrate the model error.

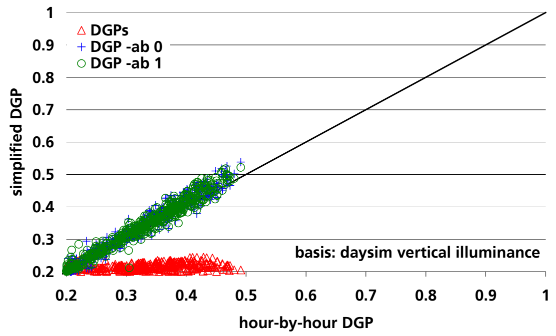

Figure 7: Fabric shading: Comparison of the DGP-values of the simplified methods (y-axis) with the reference method (hour-by-hour calculation, x-axis). The simplified method uses the DAYSIM calculated illuminance values. This is the designated application of the enhanced simplified method.

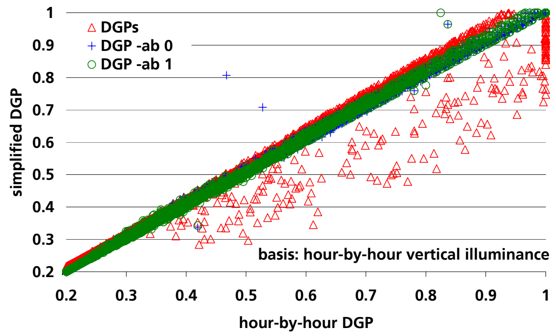

Figure 8: No shading device: Comparison of the DGP-values of the simplified methods (y-axis) with the reference method (hour-by-hour calculation, x-axis). The simplified method uses hour-by-hour calculated illuminance values in order to illustrate the model error only.

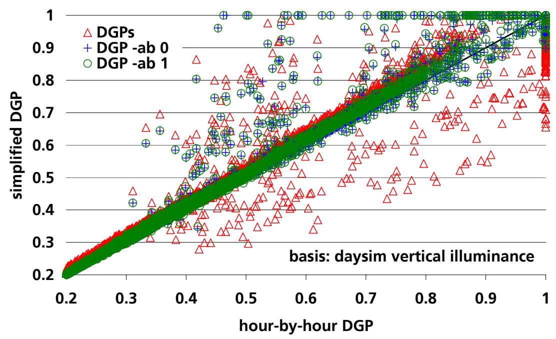

Figure 9: No shading device: Comparison of the DGP-values of the simplified methods (y-axis) with the reference method (hour-by-hour calculation, x-axis). The simplified method uses the DAYSIM calculated illuminance values. This is the designated application of the enhanced simplified method.

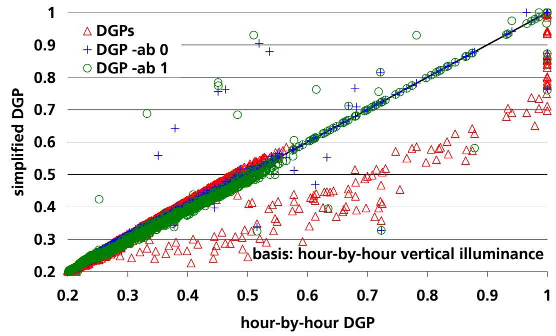

Figure 10: Venetian Blind (15° slat angle position): Comparison of the DGP-values of the simplified methods (y-axis) with the reference method (hour-by-hour calculation, x-axis). The simplified method uses hour-by-hour calculated illuminance values in order to illustrate the model error only.

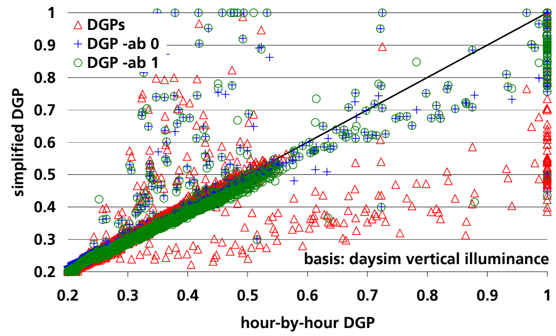

Figure 11: Venetian Blind (15° slat angle position): Comparison of the DGP-values of the simplified methods (y-axis) with the reference method (hour-by-hour calculation, x-axis). The simplified method uses the DAYSIM calculated illuminance values. This is the foreseen application of the enhanced simplified method.

Table 1 summarizes the errors for all investigated methods and shading devices. The relative root mean squared errors (rRMSE) and the averages of the relative mean bias errors (rMBE) are used to describe the errors compared to the reference method (hour-by-hour calculation). They are defined as

$$rMBE = \frac{1}{N}\sum_{i=1}^{N}\frac{DGP_i - DGP_{es,i}}{DGP_i} \qquad (3)$$

$$rRSME = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{DGP_i - DGP_{es,i}}{DGP_i}\right)^2} \qquad (4)$$

The rRMSE and rMBE values are given for the whole data when daylight is present.

The comparison of the methods (which means to use the hour-by-hour vertical illuminance as input data) shows reasonable values for the enhanced simplified methods (rRSME lower than 5%). The simplified method (DGPs) shows larger deviations to the reference method (rRSME values range between 8% and 24%).

Increasing the simulation parameter –ab from 0 to 1 shows no improvement in accuracy. This might change, if other materials with different optical properties are used.

If input data from DAYSIM is used the rRMSE is larger than using the hour-by-hour values as input. Anyhow, the rRMSE for the enhanced simplified method and -ab 0 ranges between 4.1% and 8.1%, which is still reasonable. These errors will be reduced if a future DAYSIM version increases the number of calculated sun positions.

Table 1: Error description using the relative root mean squared errors (rRMSE) and the averages of the relative mean bias errors (rMBE) for the fabric roller blind system.

INPUT DATA	METHOD	FABRIC ROLLER BLINDS rMBE [%]	rRMSE [%]
hour-by-hour	simplified DGPs	1.4%	15.7%
	enhanced simplified DGP -ab 0	-1.0%	2.8%
	enhanced simplified DGP -ab 1	1.0%	2.7%
DAYSIM	simplified DGPs	0.3%	16.4%
	enhanced simplified DGP -ab 0	0.6%	4.1%
	enhanced simplified DGP -ab 1	2.8%	4.1%

Table 2: Error description using the relative root mean squared errors (rRMSE) and the averages of the relative mean bias errors (rMBE) for the Venetian blind system (15°).

INPUT DATA	METHOD	VENETIAN BLINDS (15°) rMBE [%]	rRMSE [%]
hour-by-hour	simplified DGPs	1.8%	8.0%
	enhanced simplified DGP -ab 0	0.0%	4.9%
	enhanced simplified DGP -ab 1	-1.8%	4.3%
DAYSIM	simplified DGPs	0.5%	11.2%
	enhanced simplified DGP -ab 0	1.2%	8.1%
	enhanced simplified DGP -ab 1	-2.1%	7.9%

Table 3: Error description using the relative root mean squared errors (rRMSE) and the averages of the relative mean bias errors (rMBE) for using no shading system

INPUT DATA	METHOD	NO SHADING rMBE [%]	rRMSE [%]
hour-by-hour	simplified DGPs	9.2%	23.6%
	enhanced simplified DGP -ab 0	0.5%	1.3%
	enhanced simplified DGP -ab 1	1.2%	2.1%
DAYSIM	simplified DGPs	10.1%	23.6%
	enhanced simplified DGP -ab 0	1.6%	5.5%
	enhanced simplified DGP -ab 1	2.3%	5.8%

EVALUATION OF DYNAMIC DGP RESULTS

Up until now, no evaluation method, which takes the frequency of occurrence of glare caused by daylight into account, exists. Nevertheless, an overall assessment of glare within a time period (year, season, month) is needed to judge a façade solution not only for specific situations.

Although the underlying user assessments are only on a short-term basis, an extrapolation of results to an overall yearly glare assessment seems to be possible. The idea is to use an analogue method for the thermal assessment according to (EN 15251, 2007). In that regulation, comfort category areas are defined according to user satisfaction. Within a category, 3-5% exceedance of the threshold limit is allowed.

Based on user assessments results, daylight glare comfort classes are suggested to be defined according to the glare rating scale. The underlying user assessment data (descriptive one-way analysis) are shown in table 4. The data are acquired within a comprehensive user assessment study in test rooms, which are described in detail in (Wienold, 2009; Wienold and Christoffersen, 2006).

Table 4: Descriptive (one-way) analysis of the dgp-values and the glare rating categories of the user assessments. (avg: average value; RSMD: root mean square deviation; SE: standard error)

Glare rating	avg	RSMD	SE	95%-confidence interval lower limit	upper limit
imperceptible	0.33	0.098	0.010	0.314	0.352
perceptible	0.38	0.112	0.011	0.356	0.398
disturbing	0.42	0.148	0.015	0.390	0.448
intolerable	0.53	0.181	0.031	0.464	0.590
avg	0.39	0.098	0.010	0.314	0.352

The classes use the upper level of the 95% confidence intervals of the rating scales as DGP limits (see table 5) in order to be not too strict and to be on the safe side. These DGP limits are not allowed to exceed in more than 5% of office time. In addition to this, it is suggested to restrict the integral DGP values within this 5% interval. For this, the average DGP within the 5% should not exceed the mean DGP value of the next higher glare category (see also table 5). E.g. for the highest category following rules are set: In 95% of the office time the DGP-values must be lower or equal than the 95% confidence interval of “imperceptible”. Furthermore, in the remaining 5% of office time, the average DGP must be lower or equal the mean value of “perceptible”.

Table 5: Suggestion of the definition of daylight glare comfort classes. Both limits (DGP and average DGP within 5% band) have to be fulfilled.

	A best class 95% of office-time glare weaker than ´imperceptible´	B good class 95% of office-time glare weaker than ´perceptible ´	C reasonable class 95% of office-time glare weaker than `disturbing`
DGP limit	≤ 0.35	≤ 0.40	≤ 0.45
Average DGP limit within 5% band	0.38	0.42	0.53

The described classes can be used for fixed or variable shading systems. For the variable shading systems a reliable and valid control strategy must be applied. In the following graph, the results for the roller blind and the Venetian blinds are shown. For the Venetian blinds three control strategies and a closed fixed position (65°) are compared.

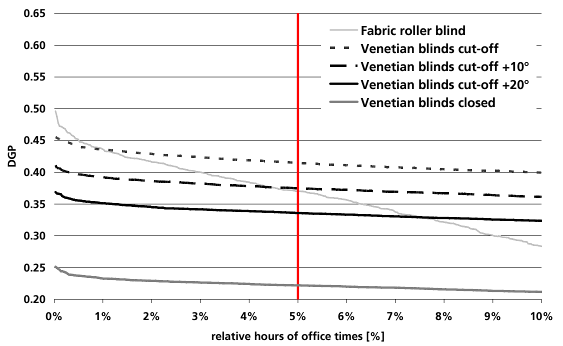

Figure 12: Result of the dynamic glare evaluation of the example systems (enhanced simplified DGP method is used). For the Venetian blinds, different control strategies are applied. The cut-off position is defined as the maximum open position of the shading device, when the direct radiation from the sun is blocked entirely. The control strategy “cut-off +10°” closes the blinds 10° more than need for the cut-off position, the “cut-off +20°” respectively 20°. The fabric roller blind is closed throughout the year.

The results show, that the control strategy has a large impact on glare evaluation. If the blinds are always closed, the occurring DGP values are extremely low, but this strategy does not seem to be very realistic. On the other hand, the comparison of Venetian blinds using cut-off-strategy with roller blinds always closed, is not fair. In this specific case, Venetian blinds offer much more view contact than roller blinds. A realistic approach would take a minimum view contact to the exterior as a lower limit of the shading position into account.

Depending on the control strategy, the same shading device can be categorized as A, B or C. This emphasizes again the need for using a realistic control strategy for the purpose of comparison.

Table 6: Tabular results of glare evaluation of the exemplar systems (enhanced simplified DGP method is used).

Variant	Max DGP value in 95% office time	Mean DGP value in 5% office time	Classification
Fabric roller blind	0.37	0.41	B
Venetian blinds cut-off	0.41	0.43	C
Venetian blinds cut-off +10°	0.38	0.39	B
Venetian blinds cut-off +20°	0.34	0.35	A
Venetian blinds closed	0.22	0.23	A

SUMMARY AND CONCLUSION

Two methods for a dynamic calculation of the DGP are presented – the simplified and the enhanced simplified DGP.

The simplified DGP is based on the vertical eye illuminance but neglects the influence of peak glare sources. Therefore, it only delivers reliable data if the façade shows neither a direct transmission component nor a peak reflection or scattering in the observer's direction. Any other method based on average luminance in the field of view (e.g. as described in (Lee et al., 2005)) is supposed to deliver similar results.

The enhanced simplified DGP uses the illuminance values from DAYSIM for the vertical eye illuminance and a simplified image to retrieve a DGP value. This method is validated against two hour-by-hour full year datasets, using a fabric and a Venetian blinds shading system. In most cases, the ambient calculation for the simplified image can be switched off. Nevertheless special façade constructions using scattering or re-directing materials probably need the use of the ambient calculation or the photon mapping algorithm for the simplified image.

For the evaluation of the dynamic DGP values, a glare rating classification based on simulations and frequency distributions is proposed. This method is suitable to compare different façade solutions as well as control strategies.

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