# **A New Daylight Glare Evaluation Method**

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# ABSTRACT

A proper glare prediction method is needed to promote visual comfort at workplaces. Only a few formulae have been proposed for discomfort glare of daylight origin, and they are inadequate in real daylight situations. No standard monitoring procedure is available for daylight glare evaluation on a comparative basis. This paper introduces an improved glare evaluation method consisting of a standard monitoring protocol and advanced formulae. The method has been tested against the existing glare evaluation system of Chauvel on different types of window size using Radiance, a lighting simulation program. Given reliable results, the DGI<sub>N</sub> procedure was coded into a small program and incorporated with Radiance to compute daylight glare indices. The method was developed with the hope that architects and lighting designers would adopt it as an easy and reliable method for evaluating discomfort glare from daylight. The future work, which is an ongoing research, is to create the use of scientific-knowledge computational tools in the later stages of design in an effort to provide optimum choices of daylighting design with respect to light level and glare using the new glare algorithm.

## List of symbols

a	Width of the window [m]		
a'	Width of the pyramid [m]		
ab	Actual glass area above 0.9 m in the facade $[m^2]$		
abτ	Effective window area [m <sup>2</sup> ]		
b	Height of the window above 0.9 m when calculating EWH [m]		
	Height of the whole window when calculating the configuration factor $\phi_i$ of the window [m]		
<i>b</i> '	Height of the pyramid [m]		
с	Width of the facade [m]		
d	Distance from the observation place to the centre of the window area [m]		
ď	Distance between the sensor and the pyramid opening [m]		
DGI <sub>N</sub>	Daylight Glare Index (N refers to "new")		
$E_{v1}$ unshielded	Average vertical unshielded illuminance from the outdoors [1x]		
$E_{\rm v2}$ unshielded	Average vertical unshielded illuminance from the surroundings [1x]		
$E_{\rm v3\ shielded}$	Average vertical shielded illuminance from the window [1x]		
EWH	Effective window height [m]		
$L_{ m adaptation}$	Average vertical unshielded luminance of the surroundings [cd m <sup>-2</sup> ]		
Lb	Background luminance [cd m <sup>-2</sup> ]		
Lexterior	Average vertical unshielded luminance of the outdoors [cd m <sup>-2</sup> ]		
L <sub>s</sub>	Source luminance [cd m <sup>-2</sup> ]		
$L_{\mathbf{W}}$	Window luminance [cd m <sup>-2</sup> ]		
$L_{ m window}$	Average vertical shielded luminance of the window [cd m <sup>-2</sup> ]		
ω	Solid angular subtense of the source at the eye [sr]		
$\omega_{\rm N}$	Solid angle subtended by the glare source (window) to the point of observation [sr]		
arOmega	Solid angular subtense of the source modified for the effect of the position of its		
	elements in different parts of the field of view [sr]		
τ	Transmission of the window plane		

#### **1. Introduction**

Building occupants generally prefer to live and work in a well daylighted space. The physical working environment, particularly the visual environment such as admission of daylight for indoor illumination, affects occupant satisfaction and worker performance and thereby also productivity. Daylight was one of the main considerations in building design to the first half of the last century. Then daylight was moved to a lower level of priority in the design process so that 20

windows at most fulfilled the user's need to have a view only. In recent years the use of daylight as a light source has won renewed interest, mainly as a result of the need for energy savings and also because of the psychophysical reasons (the psychological and physiological need for light). Nowadays daylight is again one of the most important quality characteristics of the interior lighting of buildings. The relationship between an individual and the physical environment is complex. Usually the occupant becomes conscious of the physical environment when it is uncomfortable. However, even minor effects may accumulate and lead to functional and psychological disorders when the eye keeps on trying to maintain a visual effort exceeding its physiological possibilities. If daylight is usually the preferred source of light, very high daylight availability in the interior environment is often contrary to optimum visual conditions and sunlight appears to create a whole host of psychological reactions. Glare is one of the major factors affecting visual comfort. If that problem can be solved, not only the visual comfort will be improved but also the savings of electric energy for artificial lighting can be increased due to the improved efficiency of daylight for the indoor illumination.

#### 2. The grounds for a new method

The latest glare evaluation methods have been useful in prediction of discomfort glare from artificial light sources but only a few formulae have been proposed for discomfort glare of daylight origin  $5^{(-6)+8)-11}$ . None of them predicts discomfort glare from daylight or particularly from direct sunlight. A single, internationally acceptable phenomenological glare formula and evaluation method has not been attained and no standard monitoring procedures are available. Glare is problematic also for the daylight-dependent control systems. Most of them react only to the horizontal illuminance, which however, is not sufficient for user comfort.

The subjective response to a lighting environment is complex, and impressions of glare discomfort are influenced also by other visual sensations, many psychological variables, testing conditions and individual variation<sup>4)</sup>. The net effect of these factors on the judgement process can lead to a systematic error resulting in variability of the ratings, which may not correlate the variability in the stimuli being rated. This has been the case in a number of glare assessments in artificial lighting. The situation must be even worse in real daylight. Also, it is not possible to measure directly an objective response because discomfort is experienced long before any measurable change in task performance can be detected. This gives occasion to ask whether subjective assessments are useful at all because they are not reliable. Mathematical glare prediction is objective, free from the errors that psychological and personal factors will bring.

However, the monitoring procedures for mathematical glare prediction may have problems at well. *CCD cameras* have been recently applied in glare evaluation in combination with a software to convert the signal level of the CCD camera into the actual luminance, or even to measure direct discomfort glare indices (UGR or VCP)<sup>2)</sup>. It must be taken into consideration that UGR and VCP are not valid for daylight. The relation between the signal level and the resulting luminance value differs with shutter speed, and there is a difference between the spectral sensitivity curve of the CCD camera and the one of the human eye. Therefore both an extensive calibration and  $V(\lambda)$  correction are necessary. In addition, the time-consuming mapping, the data output of relative luminance values instead of absolute values and possible insufficiency of the accuracy for the purpose all have been found disadvantages of the CCD camera. Mapping of the parameters required for the calculation of DGI with standard spot luminance meters is not sensible either because daylight circumstances may change rapidly.

Evaluation of daylight discomfort glare in test chambers with simulated windows <sup>3)-5) · 12)-14)</sup> will bring difficult problems since such a window is a large uniform and stable source of artificial light, and the psychological difference in the visual content of the field of view is obvious. In real daylighted spaces many kinds of lighting stimuli occur simultaneously. Therefore it is difficult to apply the glare index formula obtained from a laboratory experiment directly to the discomfort glare from real daylight, or to compare test results from test chambers and daylighted spaces. However, the equations of Hopkinson and Chauvel and all existing glare indices are based on experiments with uniform light sources and should therefore not be applied when discomfort glare is caused by non-uniform light sources. Also using artificial light in the room during the daylight glare measurements <sup>5)-6)11)</sup> makes it difficult to evaluate glare caused by windows.

Successful lighting and ergonomic design of workplaces requires a proper method and process for predicting glare. Daylighting design is a hard problem since its properties such as sky conditions, lighting intensity and distribution, colours and radiant energy - vary over time. The principal aim of this work was to develop a new, mathematical glare evaluation method that would be valid for direct sunlight, and to implement the new glare algorithm into a computer program using Radiance that provides luminance values. Consequently, it would be possible by this method to define with ease and reasonable accuracy the glare level caused by windows in a room space in the form of a daylight glare index and to assist the selection of daylighting systems.

#### 3. Concept of the new method

#### **3.1 Parameters**

The method is based on the *Chauvel*'s modification of the Cornell large-source glare formula (Eqn.2) to calculate daylight glare indices <sup>5)6)</sup> in ordinary work and habitable rooms. The Cornell formula of *Hopkinson* (Eqn.1) takes into consideration the source luminance and the background luminance <sup>8)-10)</sup>. The parameters in the modified version by *Chauvel* are the source luminance, the window luminance and the background luminance:

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$$G = 0.478 \sum \frac{Ls^{1.6} \times \dot{U}^{0.8}}{L_b + 0.07 \times \dot{u}^{0.5} \times Ls}$$
(1)

where

 $L_{\rm S}$ 

(1)

is the source luminance  $[cd m^{-2}]$ 

- $L_{\rm b}$  is the background luminance [cd m<sup>-2</sup>]
  - is the solid angular subtense of the source at the eye [sr]
- $\Omega$  is the solid angular subtense of the source modified for the effect of the position of its elements in different parts of the field of view [sr]

$$G = 0.478 \sum \frac{L s^{1.6} \times \dot{U}^{0.8}}{L_b + 0.07 \times \dot{u}^{0.5} \times L_w}$$
(2)

- where
- $L_{\rm S}$  is the source luminance: luminance of the patch of visible sky, of the obstructions and of the ground seen through the window [cd m<sup>-2</sup>]
- $L_{b}$  is the background luminance: luminance of the interior surfaces [cd m<sup>-2</sup>]
- $L_{\rm W}$  is the window luminance [cd m<sup>-2</sup>]
- $\omega$  is the solid angular subtense of the source at the eye [sr]
- $\Omega$  is the solid angular subtense of the source modified for the effect of the position of its elements in different parts of the field of view [sr]

However, the monitoring protocol to measure the needed parameters has not been presented either in the publications of *Chauvel* or *Hopkinson*. Moreover, the summation sign in the two formulae makes both methods mathematically anomalous; since summation has to be over solid angles in the field of view,  $\Omega$  must be to the power 1 (the summation must be proportional with the solid angle).

When compared with each other, both Chauvel's method and the new  $DGI_N$  method use the basic glare parameters: size of light source; luminance; and position of the light source in the field of view. The equations utilised in the two glare evaluation procedures contain necessarily similar components but differ fundamentally in the determination of the sources of luminance and solid angles. In the new DGI<sub>N</sub> method, the apparent solid angle  $\omega_N$  subtended by the window (Eqn.11), and the solid angle  $\Omega_{\rm pN}$  subtended of the source (Eqn.12) are modified to include the effect of the observation position (the position of the measuring equipment) and configuration factor. Therefore they reflect better the effect of the geometrical situation than  $\omega$  and  $\Omega$ . The weight of the background luminance is large in Chauvel's method, which affects the average luminance of the visual field or adaptation luminance. A large glaring source such as a window also covers a too large area on the retina to be clearly distinguished from the background. Therefore the background luminance cannot be

accurately defined and was rejected in this new method. Instead of that, the term of adaptation luminance (including the contribution of the source) is introduced because of the greater impact the immediate surround luminance has on discomfort glare sensation in comparison to the background luminance. The change of background luminance into adaptation luminance reflects totally other strategy than that of previous methods.

The parameters here are:

- the *window luminance* (Eqn.5): the source luminance
- the <u>adaptation luminance</u> (Eqn.6): the luminance of the surroundings including reflections from the internal surfaces
- the <u>exterior luminance</u> (Eqn.7): the luminance of the outdoors, caused by direct sunlight, diffuse light from the sky and reflected light from the ground and other external surfaces

# 3.2 Calculation procedure

The room can be occupied or unoccupied, with or without shading devices in the window, but the monitoring protocol assumes the room to have only vertical window(s). There are no limitations for the window size, shape, position or orientation (Figure 1). Because the measurement position is in the same horizontal plane as the centre of the window, the method is not, however, recommended for windows right under the ceiling such as clerestory windows. This is because the difference between the measurement position and the position of the observer's eyes would be too big. In that case, the measurement could predict less glare than the observer would perceive when looking up towards the window and a brighter part of the sky. On the other hand, windows like that would be at the periphery of the visual field and would be notably less glaring. In regard to lighting, no artificial lighting is permitted but both daylight and sunlight can be measured. This is an advantage over the other daylighting calculations which all have assumptions not to include direct sunlight portion into a room <sup>15)16</sup>.



Figure 1 The procedure can be used for various window sizes and shapes

The degree of discomfort glare is reflected in Daylight Glare Index,  $DGI_N$  (where N refers to "new"). As stated earlier,  $\Omega$  must be to the power 1. This can be easily done since:

$$10\log_{10}\left(L_{\text{exterior}}^{1.6} \times \dot{U}_{\text{pN}}^{0.8}\right) = 8\log_{10}\left(L_{\text{exterior}}^{2} \times \dot{U}_{\text{pN}}^{1}\right)$$
(3)

The  $DGI_N$  can be calculated as:

$$DGI_{\rm N} = 8\log_{10} \left( 0.25 \frac{\Sigma \left( L_{\rm exterior}^2 \times \dot{U}_{\rm pN} \right)}{L_{\rm adaptation} + 0.07 \left( \Sigma \left( L_{\rm window}^2 \times \omega_{\rm N} \right) \right)^{0.5}} \right)$$
(4)

The three parameters included in Eqn.4 are calculated as follows:

$$L_{\text{window}} = \frac{E_{\text{V3,sheilded}}}{2\phi \times \delta}$$
(5)

where  $L_{window}$  is the average vertical shielded luminance of the window [cd m<sup>-2</sup>]

 $E_{v3 \text{ shielded}}$  is the average vertical shielded illuminance from the window [1x]

$$L_{\text{adaptation}} = \frac{E_{\text{V2,unsheilded}}}{\pi} \tag{6}$$

where  $L_{adaptation}$  is the average vertical unshielded luminance of the surroundings [cdm<sup>-2</sup>]  $E_{v2 \text{ unshielded}}$  is the average vertical unshielded illuminance from the surroundings [lux]

$$L_{\text{exterior}} = \frac{E_{\text{V1,unsheilded}}}{2(\pi - 1)}$$
(7)

where  $L_{\text{exterior}}$  is the average vertical unshielded luminance of the outdoors [cd m<sup>-2</sup>]  $E_{\text{vl unshielded}}$  is the average vertical unshielded illuminance from the outdoors [lx]

The configuration factor  $\phi_i$  of the window from the observation place (the position of the measuring equipment) is calculated as follows <sup>17</sup>:

$$A = \frac{X}{\sqrt{1 + X^{2}}} \qquad B = \frac{Y}{\sqrt{1 + X^{2}}}$$
$$C = \frac{Y}{\sqrt{1 + Y^{2}}} \qquad D = \frac{X}{\sqrt{1 + Y^{2}}} \qquad (8)$$

$$\ddot{O}_i = \frac{A \arctan B + C \arctan D}{\pi} \tag{9}$$

$$=\frac{a}{2d} \qquad \qquad Y = \frac{b}{2d} \tag{10}$$

whereais the width of the window [m]bis the height of the window [m]dis the distance from the observationto the centre of the window area

X

is the distance from the observation place to the centre of the window area [m]

The calculation of the solid angle and form factors can easily lead to mistakes. The apparent solid angle  $\omega_N$  subtended by the window, and the solid angle  $\Omega_{\rm PN}$  subtended of the source are here defined accurately using particular formulae (Eqn.10,11) developed for this purpose <sup>15)16</sup>. However, in the modification by *Chauvel* these parameters are not calculated but estimated:  $\Omega$  is derived from the Petherbridge solid angle diagram,  $\omega$  is taken from the semi-sinusoidal Waldram solid angle diagram, and  $L_b$  is derived from the BGI nomograph.

No advice was found in the literature as to how many segments the window should be divided when calculating  $\omega$ and  $\Omega^{1}$ . In this research, the consistency of  $\omega_N$  was tested by calculating the value for an undivided window (1.55 x 1.35 m) and for the same window divided into four segments. The  $\omega_N$ values were nearly identical: 0.3841 for the undivided window, and 0.3835 as a sum of the four quarter parts (0.096 for each). The number of segments does not have any essential influence on  $\omega_N$ . This suggests that this is a stable part of the calculation.  $\omega_N$  for a whole window is used in these calculations <sup>16</sup>.

$$\omega_{\rm N} = \frac{ab\cos(\arctan(X))\cos(\arctan(Y))}{d^2}$$
(11)

where  $\omega_N$  is the solid angle subtended by the glare source (window) to the point of observation [sr] accurate to 1% for X, Y < 0.5 accurate to 5% for X, Y < 1

$$\Omega_{\rm pn \ window} = 2 \ \pi \ \Phi_i$$
(12)  
accurate to 1% for X, Y < 0.1

Eqn.10 provides accurate results also in comparison with computer calculations using the "Simpson rule" integration (step by step for single elements). The arguments of both angle functions (Eqn.10,11) are only dependent on the horizontal and vertical dimension of the window. So, if both values for width and height of the window will be exchanged, nevertheless the same solid angle should result <sup>15)16)</sup>.

# 3.3 Measuring tools

Daylight discomfort glare is defined by a special arrangement of three illuminance sensors inside the room. A

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difficult series of frequent spot luminance measurements is not required but the novel monitoring methodology calls for continuous, automatic measurement of shielded and unshielded vertical illuminances from which the window luminance, adaptation luminance and exterior luminance can be derived and the  $DGI_N$  to be calculated. The sensors should be spot sensors (concentrated into a spot, see Figure 3b). The sensors are mounted vertically on a tripod according to the midpoint of the window looking at its centre (Figure 2). This is because the luminance distribution within the window plane is non-uniform and can therefore cause more glare than uniform light sources when positioned perpendicular to the line of sight <sup>18)</sup>. The glare sensation is largest at 0° from the viewpoint, and here the objective is to define the worst-case condition only. However, the calculation of  $DGI_N$  is based on the average luminance of the window wherefore small areas of high brightness within the overall window area are not considered. Photographs are used to record additional glare phenomena. Worth noticing is also that a real test subject could not be placed facing the window without influencing the results through the visual and psychological factors and disability glare that would be obvious in the presence of direct sunlight.



Figure 2 A set of three vertical sensors to evaluate discomfort glare

- Location of the sensors
- the unshielded sensor N° 1 (not necessarily mounted on a tripod but can be placed separately) is placed close to the middle point of the window at a distance of 0.20 m from the glazing
  - $\Rightarrow$  to measure the exterior illuminance
- the unshielded sensor N° 2 is placed at the level of the opening of the shield for the sensor N° 3 (Figure 3 b,c) to cover a semicircular 180° area

⇒ to measure the adaptation illuminance

- the shielded sensor N° 3 (Figure 3 a,b,c) is placed at the level of the midpoint of the window and is adjusted with a shield, black pyramid (with mat finish free of any reflections), to cover the rectangular window entirely without gathering light from the surroundings
  - $\Rightarrow$  to measure the window illuminance





#### Figure 3 a

e 3 a The black pyramid to shield the sensor  $N^{\circ}$  3

- **b** The unshielded sensor  $N^{\circ}$  2 and the shielded sensor  $N^{\circ}$  3
- c The unshielded sensor N° 2 placed on the level of the pyramid opening





# The distance between the window and the shielded sensor

To establish an appropriate procedure for the measuring of the parameters on a comparative basis under real sky conditions, subdivision of a room into three specific lighting areas (*the high daylight area, medium daylight area and low daylight area*) based on the effective window height, EWH, is recommended <sup>7)</sup>. The subdivision of a room is made according to the dimensions of the window and facade as it is shown in Figure 4. Room dimensions, however, are disregarded because the target is to define glare situation only in the vicinity of the window.

The dimensions of the window and facade are then used in Eqn.12:

EWH	$=\frac{ab \tau}{c}$	(12)
where	EWH abτ	is effective window height [m] is effective window area [m <sup>2</sup> ]
	ab	is the actual glass area above 0.9 m in the facade $[m^2]$
	а	is the width of the window [m]
	b	is the height of the window above 0.9 m [m]
	τ	is the transmission of the window plane
	с	is the width of the facade [m]

According to the value of EWH:

- high daylight area (where artificial light is not usually needed) starts at the facade and has a depth of appr.  $2 \times EWH$
- intermediate daylight area starts at the border of the high daylight area and has a depth of appr. 1.5
   × EWH
- *low daylight area* (where artificial light is usually needed) is the remaining part of the room

The perceived degree of discomfort glare is generally lower at the back of the room than near the facade <sup>13)</sup>. In addition, the sky can usually be seen only from the high and intermediate daylight area. As the glaring sky occupies the largest part of the visual field in the high daylight area, wherefore it is disliked as a working place, the back edge of the intermediate daylight area was considered suitable as the position of the shielded sensor N° 3.

The measurement position based on EWH is completely different from the "mid-point of the walls" standard that has been used in electric lighting. The evaluation positions in the centre of each wall viewing normal to the wall is inadequate for daylight conditions where the light distribution as function of the distance from the window is to be determined for the needs of daylight control.

## Geometric description of the shield

When the window dimensions are known and the distance between the window and the shielded sensor has thereby been determined, it is possible to shape the pyramid according to that information (Figure 5). The shape of the shield, however, can be also different from pyramid (e.g. a cube), provided that the sensor is totally covered by the shield and can see only the window, and the inner surface of the shield is black and free of any reflections. The shape of the opening of the shield, and the distance between the opening and the shielded sensor, are essential and are derived from Eqn.13,14. Thus the distance can be calculated according to Eqn.15 and the dimensions of the shield opening according to Eqn.16.



# Figure 5 Similarity of triangles is the base for shaping the opening of the pyramid

Supposed that the sensor shielded by the pyramid is concentrated into a spot:

$$\frac{a}{2d} = \tan \alpha = \frac{a'}{2d'} \qquad \frac{b}{2d} = \tan \beta = \frac{b'}{2d'}$$
(14)

$$\frac{a'}{a} = \frac{d'}{d} = \frac{b'}{b} \tag{15}$$

Thus the distance between the opening and the shielded sensor can be calculated:

$$d' = \frac{db'}{b} \tag{16}$$

and the dimensions of the shield opening can be calculated as:

$$a' = \frac{ad'}{d} \qquad b' = \frac{bd'}{d} \tag{17}$$

nere	a	is width of the window [m]
	a'	is width of the pyramid [m]
	<b>b</b>	is height of the window [m]
	<i>b</i> '	is height of the pyramid [m]
	d	is distance between the window and the
		shielded sensor [m]
	ď	is distance between the sensor and the
		pyramid opening [m]

Example

wl

Supposed that (Figure 6):

the room has dimensions of 3.7m x 2.7m x 2.68m

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# and the window is 1.55m x 1.35m 75% transmittance (for visible light) for the double clear glazing

the distance (d) between the shielded sensor  $N^{\circ}$  3 and the window, as well as the shape of the shield, will be determined by means of the *EWH* as follows:

 $EWH = (1.55 \text{ m x } 1.35 \text{ m x } 0.75) : 2.66 \text{ m} = 0.59 \text{ m} \approx 0.60 \text{ m}$ and thereby the high daylight area has a depth of 1.20m the intermediate daylight area has a depth of 0.90m

Thus the correct distance (d) between the shielded sensor and the window is on the back edge of the intermediate daylight area:

1.20m + 0.90m = 2.10m (Figure 6)



Figure 6 Exact dimensions of the test room

The midpoint of the window, and thus the level of the sensor  $N^{\circ}$  3, is at a height of 1.58m (Figure 6). The distance between the shield opening and the sensor inside was chosen to be 0.17m. Thus the dimensions of the opening are according to Eqn.16 (Figure 7):

$$a' = \frac{ad'}{d} = \frac{1.55 \text{m} \times 0.17 \text{m}}{2.10 \text{m}} = 0.12 \text{m}$$

$$b' = \frac{bd'}{d} = \frac{1.35 \text{m} \times 0.17 \text{m}}{2.10 \text{m}} = 0.11 \text{m}$$



Figure 7 The dimensions of the shield

# 4. Conclusions

The author considers that discomfort glare can be predicted mathematically. Objective glare evaluation is an essential prerequisite for user comfort in modern buildings with innovative daylighting systems and daylight responsive lighting controls. The only reliable data for lighting control can be derived (Daylight Glare Index), not from variable subjective assessments, but there is a need on more accurate DGI. The change from the obsolete *Hopkinson*'s formula through *Chauvel*'s formula to the proposed *DGI* method is a great improvement.

The new  $DGI_N$  procedure appears to yield sensible and consistent glare values, which is invaluable in the assessment of daylight system performance. The  $DGI_N$  will grow along with the increase in vertical illuminance on the window, the source luminance, whereas the DGI of *Chauvel* behaves just the opposite; the higher is the vertical illuminance, the smaller will be the glare sensation. Moreover, scatter of the DGIvalues of *Chauvel* is very large. Because of these features, it is impossible to apply *Chauvel*'s formula to any daylighting control system. The new  $DGI_N$ , on the other hand, may have future applications in lighting control systems; the sensors of daylight responsive lighting controls react on the illuminance level, and in the future also to glare to improve visual comfort. This is possible by using a new glare algorithm based on the proposed new method. The new method was developed with the hope that architects and lighting designers would adopt it as the method for the assessment of daylight system performance. This could make the design and selection of daylighting controls easier. A tool for lighting designers, engineers and architects is now in process of preparation. The tool is expected to be a welcome instrument for all of those who are struggling to create ergonomically optimal working environment where maximum visual comfort and maximum productivity can be achieved.

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