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Laouadi, A.; Parekh, A.

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COMPLEX FENESTRATION SYSTEMS: TOWARDS PRODUCT RATINGS FOR INDOOR ENVIRONMENT QUALITY

Abdelaziz Laouadi^(a) and Anil Parekh^(b)

^(a) Indoor Environment Research Program

Institute for Research in Construction, National Research Council Canada

1200 Montreal Road, Ottawa, Ontario, Canada, K1A 0R6

Fax: +1 613 954 3733. Tel: +1 613 990 6868. Email: aziz.laouadi@nrc-cnrc.gc.ca

^(b) Sustainable Buildings and Communities

CANMET Energy Technology Centre, Natural Resources Canada

580 Booth Street, 13th Floor, Ottawa, Ontario, K1A 0E4

Tel: +1 613 947 1959. Email: AParekh@NRCan.gc.ca

ABSTRACT

Complex fenestration systems (CFS) include windows featuring complex glazing such as translucent and transparent insulation, solar control films, patterned or decorative glass, in-between pane shades, etc. CFS are believed to exhibit superior energy performance, but may have adverse effects on environmental features important for building-occupant satisfaction requirements such as the outdoor view (connection to outside), indoor view (feeling of privacy), luminance (major factor for discomfort glare), and light diffusion quality (relates to uniformity of illuminance on work plane). This paper is part of a larger effort to rate complex fenestration systems for energy performance and indoor environment quality (IEQ). In the end, IEQ ratings must be derived from direct studies of how building occupants perceive the indoor environment conditions created by the installed fenestration product. As a first step, this work tackles the theoretical development of new metrics to rate CFS with regards to IEQ, namely the view impairment index, luminance index and light diffusion quality index. The new indices are applied to some typical CFS, namely a diffuse window, and a clear window combined with an interior shading screen, and integrated perforated Venetian blinds. The results show that the diffuse window may increase the luminance by more than 100% under clear sky conditions when compared with a clear window with a similar light transmittance. White coloured Venetian blinds may increase the window luminance by up to 50% and reduce the outdoor view by up to 66% as compared with a clear window with a similar light transmittance.

1 Introduction

The need for energy conservation in buildings and better indoor environment quality has spurred innovations in window design. Complex fenestration systems (CFS) refer to any window product that incorporates a non-clear (non-specular) layer in the glazing assembly or in its attachments. Examples include the combination of the advanced technologies of high performance clear windows (e.g., low-e coating, spectrally selective glazing) with innovative glazing materials such as smart glazing, translucent or transparent insulation, solar control films doped with nano-particles, patterned/fritted glass, etc. Window attachments such as shading devices are combined with the advanced clear window products to make efficient-use of daylight and reduce the unwanted solar heat gains and potential glare problem associated with the clear window product alone. CFS have usually superior thermal, lighting and energy performance (e.g., low thermal transmittance, good illuminance uniformity on work planes and low annual energy use), but may create environmental conditions that have adverse effects on indoor environment quality (IEQ) aspects such as view-through and luminance (important factor for discomfort glare). Fenestration products that improve the IEQ can expect accelerated market penetration while any detrimental effect on the IEQ can have severe effects not only on product commercialization and market acceptance, but also on the energy performance of the installed product in buildings. Therefore, product ratings of CFS should include not only the energy performance characteristics, but also factors that may affect the indoor environment quality.

The customary optical performance indicators, originally developed for clear fenestration products, include the visible transmittance and the solar heat gain coefficient. These indicators are, however, unable to indicate the outdoor view (connection to outdoor), indoor view (feeling of privacy), luminance (leading to discomfort glare), and light diffusion quality (relating to illuminance uniformity on work planes) associated with complex fenestration products. As a matter of fact, complex fenestrations may increase the potential risk of discomfort glare by increasing the window luminance, impair the outdoor/indoor view and increase the illuminance uniformity on work planes due to forward light scattering.

There are a few studies related to IEQ performance of CFS. Early subjective studies on view through clear windows showed that the window shape and size and the visual contents of outdoor scenes are important to occupant satisfaction^(1,2). Windows with natural views were found to enhance work, wellbeing and health of building occupants^(3,4). Visibility studies of clear windows equipped with interior shading screens were found to decrease when the view line direction is off the window surface normal^(5,6). The studies also found that the luminance distribution over the screened windows was essentially non-uniform, and the higher the non-uniformity of luminance the lower the perceived glare. Subjective studies on discomfort glare from windows showed that the perceived glare is much lower than the predicted glare using the established glare rating systems⁽⁷⁻⁹⁾. This difference was mainly attributed to the fact that existing glare rating systems were developed for small size artificial lighting sources and, therefore,

cannot be applied to large sources such as windows. Tentative modifications to existing glare rating models were proposed, but the fact still remains: predicted glare is weakly correlated with perceived glare, particularly with complex windows with non-uniform luminance⁽⁹⁾. There is growing evidence that other non-luminous factors such as outdoor views (view contents, quality of view), sunbeam light as opposed to diffuse light, and environmental aesthetic look could compound the sensation of glare⁽⁸⁾. This suggests further research on the psychological effects of window functionalities (view, privacy, daylighting) on the perceived environmental conditions created by the window.

2 Objectives

This work is part of a larger effort to rate complex fenestration products for energy performance and indoor environment quality. The indoor environment quality ratings are the missing components in the current product rating standards. In the end, indoor environment quality ratings must be derived from direct studies of how building occupants perceive the indoor environment conditions created by the installed fenestration product. In an accompanying paper by the authors, general optical models were developed to compute the overall optical and forward/backward light scattering characteristics (transmittance, reflectance, layer absorptance, haze/gloss) of complex fenestration systems. This paper tackles the theoretical development of new metrics to rate complex fenestration systems with regards the indoor environment quality. The specific objectives are:

- To develop new indices to rate CFS with regards to the outdoor view (connection to outdoor), indoor view (feeling of privacy), luminance (major factor of discomfort glare) and light diffusion quality (related to illuminance uniformity on work planes).
- To apply the new ratings to typical diffuse window and clear window combined with interior shading screen and integrated perforated Venetian blinds.

3 Optical Model of Complex Fenestration Systems

The details of the optical models of complex fenestration systems may be found in an accompanying paper by the authors. The models are based on the optical characteristics (transmittance, reflectance) and the forward/backward haze properties of each glazing layer making up the glazing assembly. The forward and backward haze characterizes the scattering effect of the glazing material on the transmitted and reflected light energy, respectively. The models are implemented in the research version of SkyVision⁽³⁾.

4 IEQ metrics of Complex Fenestration Systems

In this section, we present new indices of merit, potentially related to building-occupant satisfaction, namely the view impairment index, which is directly related to the outdoor view and privacy, window luminance index, and light diffusion quality.

4.1 View impairment index

The human visual system distinguishes objects through their luminance contrast and colour difference with respect to their background⁽³⁴⁾. The luminance contrast indicates the relative difference between the luminance of the object and the background luminance. Therefore, any change in the luminance contrast of objects around its actual value (in the absence of a window) will introduce a perturbation to the view of objects seen through a window. We define the view impairment index as the reduction of the actual view of objects seen through a window under given surrounding lighting conditions. How people respond to this view reduction is, however, not addressed in this paper. In other words, the view impairment index has purely objective meaning. As a matter of fact, view reduction is common in the real world, but under some circumstances, this reduction is not perceived by the human visual system. For example, veiling reflection from objects with glossy surfaces may decrease the visibility of objects, depending on the light source luminance and surface specular reflectance. However, veiling reflection from matte surfaces under a diffuse light source is so weak it cannot be detected by the visual system⁽³⁷⁾. Veiling reflection from window surfaces has the same effect as veiling reflection from object surfaces as both reduce the luminance contrast of objects. It should be noted that the view impairment index does not portray a permanent reduction to the view of objects; the view impairment of objects prevails as long as the lighting conditions do not change, and the extent of the view impairment may be reduced if one of the lighting conditions changes or ceases to exist.

Consider a window placed between two lighting conditions as shown in Figure (1): exterior conditions consisting of sunbeam light, and sky and ground diffuse light; and interior conditions consisting of a beam light source and a diffuse surrounding background. The window may introduce a modification to the view of objects through the scattering of the incoming light towards the observer's eye or veiling specular reflection from the window surface. The window light scattering reduces the contrast of the object seen through the window and the veiling specular reflection disturbs the view by superimposing the image of the light source on the target image, giving the latter a blurry appearance. The view impairment index is expressed as the ratio of the perturbation luminance (scattered and veiling luminance) to the sum of the object and perturbation luminance exiting from the window towards the observer's eye:

$$VRI(v) = \frac{L_{obj}(v) \cdot VT_f(v) \cdot H_{f,t}(v) + L_{b,sc} + L_{b,veil,dif} + L_{b,veil}(v, \theta_l)}{L_{obj}(v) \cdot VT_f(v) + L_{b,sc} + L_{b,veil,dif} + L_{b,veil}(v, \theta_s)} \quad (1)$$

where:

$H_{f,t}$: window transmission haze for light incident on the front (exterior) window surface along the view line direction (dimensionless);

L_{obj} : luminance of the target object seen through a window along a given view line (cd/m^2);

$L_{b,sc}$: scattered luminance exiting from the back (interior) surface of the window (cd/m^2);

$L_{b,veil}$: veiling specular luminance from the beam light source reflected from the back (interior) surface of the window (cd/m^2);

$L_{b,veil,dif}$: veiling specular luminance from diffuse background lighting (cd/m^2);

VRI : view impairment (reduction) index along a given view line direction (dimensionless);

VT_f : window transmittance for light incident on the front (exterior) window surface along the view line direction (dimensionless);

v : view angle with respect to the window surface normal (radians);

θ_l : incidence angle of the light source (radians);

θ_s : incidence angle of beam sunlight (radians).

By considering Figure (1), the scattered and veiling luminances can be expressed as follows:

$$L_{b,sc} = \left[\begin{aligned} &E_{sun} \cdot \cos(\theta_s) \cdot VT_f(\theta_s) \cdot H_{f,t}(\theta_s) + E_{e,dif} \cdot VT_{f,d} \cdot H_{f,t,d} + \\ &L_s \cdot \Omega_s \cdot \cos(\theta_l) \cdot VR_b(\theta_l) \cdot H_{b,r}(\theta_l) + E_{i,dif} \cdot VR_{b,d} \cdot H_{b,r,d} \end{aligned} \right] / \pi \quad (2)$$

$$L_{b,veil}(v, \theta_l) = \begin{cases} L_s(\theta_l) \cdot VR_b(\theta_l) \cdot [1 - H_{b,r}(\theta_l)] & \text{if view direction } (v) = \text{reflection direction } (\theta_l) \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

$$L_{b,veil,dif} = E_{i,dif} / \pi \cdot VR_b(v) \cdot [1 - H_{b,r}(v)] \quad (4)$$

where:

$H_{f,t,d}$: window transmission haze for diffuse light incident on the front (exterior) window surface (dimensionless);

$H_{b,r}$: window reflection haze for beam light incident on the back (interior) window surface (dimensionless);

$H_{b,r,d}$: window reflection haze for diffuse light incident on the back (interior) window surface (dimensionless);

- L_s : luminance of the light source along a given incidence direction (cd/m^2);
- $E_{e,dif}$: diffuse exterior illuminance from the sky and ground received at the front surface of the window (lux);
- $E_{i,dif}$: diffuse interior illuminance from the surrounding background received at the back surface of the window (lux);
- E_{sun} : normal illuminance of the sunbeam light (lux);
- VR_b : window visible reflectance for light incident on the back window surface (dimensionless);
- $VR_{b,d}$: window visible reflectance for diffuse light incident of the back window surface (dimensionless);
- $VT_{f,d}$: window visible transmittance for diffuse light incident on the front window surface (dimensionless); and
- Ω_s : solid angle subtended by the light source seen through the window surface (steradians).

Figure 1 Factors affecting the view of objects seen through a window

Equation (1) stipulates that the view impairment index varies between 0 and 1. $VRI = 0$ indicates that the actual view of objects is not impaired (full view). $VRI = 1$ indicates, however, that the actual view of objects is fully impaired (objects are not visible through the window). It should be noted that translucent windows with transmission haze $H_t = 1$ fully impair the view, irrespective of the surrounding lighting conditions ($VRI = 1$). The view of objects seen through a clear window ($H_t = 0$) depends, however, on the surrounding lighting conditions. In the following, we will consider how the characteristics of a window product affect the outdoor and indoor view under given surrounding lighting conditions.

4.2 Outdoor View Index

Outdoor view is desirable in both residential and commercial buildings. There are a number of factors that may influence the outdoor view, namely the optical characteristics and colour of the window glazing product, the size and shape of the window opening^(1,2), the surrounding lighting levels, and the contents of the outdoor scene. This paper excludes the size and shape of the window opening and the content of the outdoor scene from the outdoor view rating since these factors are not defined yet for window product rating purposes. In this context, we define the outdoor view as the ability of a person situated indoors to see outdoor objects through the window under given lighting conditions during daytime. Seeing fine details of objects is irrelevant in this definition. Moreover, the observer should be placed far enough from the window so that the characteristic size of glazing objects causing light scattering should not be seen (that is lower than the visual size threshold). In addition, luminance of target objects should be higher than the visual luminance threshold to cause a stimulus to the visual system. The outdoor view is dependent on the relative position of the outdoor object with respect to the observer's eye. For a seated person where the direct line of view is perpendicular to the window, one may consider the normal (perpendicular) outdoor view. However, if the outdoor scene is desired over a field of view, one may consider the average outdoor view over the viewing hemisphere.

The outdoor view index in this paper has a purely objective meaning. The subjective evaluation of the quality of view based on occupant perception may be related to the objective index, but is also related to many other factors such as individual attitudes, prior experience, view content, etc. The outdoor view index (OVI) may be expressed as a function of the view impairment index as follows:

$$OVI_n = 1 - VRI_n \quad (5)$$

for the normal view (view line perpendicular to the window surface); and

$$OVI_d = 1 - VRI_d \quad (6)$$

for the average view over the viewing angles, with VRI_d is the average of VRI over all viewing angles, given by the following equation:

$$VRI_d = \frac{1}{VT_{f,d}} \int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi/2} VRI(\theta, \varphi) \cdot VT_f(\theta, \varphi) \cdot \sin 2\theta \cdot d\theta \cdot d\varphi \quad (7)$$

where:

OVI_n : normal outdoor view index (dimensionless);

OVI_d : average outdoor view index (dimensionless);

ϕ : azimuth angle of the incident light on the window surface (radians);

θ : incidence angle of light (radians).

For fenestration product rating purposes, we evaluate the outdoor view index of a distant object situated in the sky vault under standard sky conditions and the sunbeam light is parallel to the view line direction. The indoor lighting conditions, which are usually significantly lower than the outdoor lighting, would not have a significant effect on the outdoor view. Under given sky conditions, the normal view impairment index takes the following form:

$$VRI_n = \frac{VT_{f,n} \cdot H_{f,t,n} \cdot (\pi + E_{bh}/L_h) + E_{dh}/L_h \cdot VT_{f,d} \cdot H_{f,t,d}}{VT_{f,n} \cdot (\pi + E_{bh}/L_h \cdot H_{f,t,n}) + E_{dh}/L_h \cdot VT_{f,d} \cdot H_{f,t,d}} \quad (8)$$

where:

E_{bh} : sunbeam illuminance received on a horizontal plane (lux);

E_{dh} : diffuse illuminance from sky light received on a horizontal plane under a given sky condition (lux);

$H_{f,t,n}$: window transmission haze for normal beam light incident on the front window surface (dimensionless);

L_h : sky horizontal (or zenith) luminance, excluding sunbeam light (cd/m^2);

$VT_{f,n}$: window visible transmittance for normal beam light incident on the front window surface (dimensionless).

The ratios E_{bh}/L_h and E_{dh}/L_h are equal to 6.155 and 0.967 under the CIE clear sky conditions, and to 0.0 and 2.445 under the CIE standard overcast conditions, respectively.

4.3 Indoor View index

The indoor view index may be expected to relate to privacy, which is also important as the outdoor view in residential and commercial buildings. The more obscured the indoor view the better the privacy. It should be noted, however, that the privacy might not be a linear function of the indoor view index as the privacy is inherently a subjective quantity. The indoor view index is evaluated when the target object is situated indoors and the observer outdoors. Surrounding illuminances are, thus, important for the evaluation of the indoor view index (or privacy). While diffuse window products offer no indoor view (full privacy), the indoor view through clear windows is entirely dependent on the indoor and outdoor illuminances. The indoor view index (IVI) is expressed by the same relations as the outdoor view index (equations 5 to 7), but with accounting for the indoor illuminance levels. For fenestration product rating purposes, we evaluate the

indoor view index (IVI) of an indoor object having the same luminance as the indoor background lighting with no beam light sources. The outdoor illuminances are those of standard sky conditions and sunlight parallel to the view line. In this case, the normal view impairment index takes the following form:

$$VRI_n = \frac{VT_{b,n} \cdot H_{b,t,n} + E_{bh} / E_{i,dif} \cdot VR_{f,n} \cdot H_{f,r,n} + E_{dh} / E_{i,dif} \cdot \{VR_{f,n} \cdot [1 - H_{f,r,n}] + VR_{f,d} \cdot H_{f,r,d}\}}{VT_{b,n} + E_{bh} / E_{i,dif} \cdot VR_{f,n} \cdot H_{f,r,n} + E_{dh} / E_{i,dif} \cdot \{VR_{f,n} \cdot [1 - H_{f,r,n}] + VR_{f,d} \cdot H_{f,r,d}\}} \quad (9)$$

where:

$H_{b,t,n}$: window transmission haze for normal beam light incident on the back window surface;

$H_{f,r,n}$: window reflection haze for normal beam light incident on the front window surface (dimensionless);

$H_{f,r,d}$: window reflection haze for diffuse light incident on the front window surface (dimensionless);

$VR_{f,n}$: window visible reflectance for normal beam light incident on the front window surface (dimensionless);

$VR_{f,d}$: window visible reflectance for diffuse light incident on the front window surface (dimensionless);
and

$VT_{b,n}$: window visible transmittance for normal beam light incident on the back window surface (dimensionless).

Equation (9) stipulates that the indoor view index of clear windows is dependent on the ratio of the outdoor diffuse horizontal illuminance to the indoor background illuminance. For lower outdoor-to-indoor illuminance ratios (e.g. at nighttime), the indoor view is not significantly altered (full indoor view, $VRI \rightarrow 0$). However, for higher ratios (e.g. at daytime, particularly under overcast or partly cloudy sky conditions), the indoor view may change due mainly to the veiling reflection from the window surface (blurry, or no indoor view, $VRI \rightarrow 1$). For equal indoor and outdoor illuminances such for a window between two indoor spaces, the view impairment index takes the form $VRI = VR_{f,n} / (VT_{b,n} + VR_{f,n})$. The higher the window reflectance, the better the privacy. For single and double clear windows, the VRI is equal to 0.08 ($IVI = 0.92$) and 0.14 ($IVI = 0.86$), respectively. At these levels of VRI, the view of objects through the window might be acceptable under such illuminances.

4.4 Luminance Index

The window luminance is a dominant factor for discomfort glare calculation^(11,13). Some regulations, particularly in Europe, use the window luminance limiting system as a measure of discomfort glare⁽⁹⁾. Discomfort glare not only affects the building occupant satisfaction, performance and health^(12,14), but also the energy performance of the installed window product. For example, reducing the risk for discomfort

glare may result in the reduction of daylight and solar heat gains, which may therefore result in increasing seasonal building energy use. Previous studies for artificial lighting^(13,15) showed that the discomfort glare rating is proportional to the luminance (or intensity) and size of the light sources, the light source position with respect to the line of sight, and the background indoor luminance. Glare from windows would depend, among other factors as above, on the luminance and size of the window and/or the outdoor light sources^(7,16). For clear window products, where the light direction of the source is not altered after transmission, the luminance (or intensity) and size of the outdoor sources become the driving factors for discomfort glare. In this case, the window product contributes to reduce the source luminance, and the window size may become irrelevant for light sources of smaller apparent size than the window. However, for fully diffuse window products where the light direction of the source is altered after transmission, the source size and its luminance are irrelevant as the window luminance becomes only dependent on the amount of lighting energy falling on it. In this case, the window may increase or reduce the luminance along the line of view to the outdoor source. The size of the window thus becomes an important parameter for discomfort glare. If two window products are to be compared when the indoor background lighting conditions are kept identical (i.e., using daylight-linked controls), the relative change in the discomfort glare rating from one product to another will depend only on the luminance performance of the two window products. For scattering window products, the window luminance is made up of two components: (1) a beam component along the line of view to the outdoor light source, and (2) a diffuse component. The beam luminance component depends on the luminance of the outdoor light source, whereas the diffuse component depends on the amount of light falling on the window surface from the sky, ground-reflected and sun beam light. For window product rating purposes, we exclude the sunbeam light in the beam luminance component as the sun source subtends a very small angle (0.5°) with very high luminance compared to the sky patch visible from the window, but include it in the diffuse luminance component. If direct sun is visible to the occupant's eye, there will be always a glare problem requiring an opaque shading device. We therefore define the window luminance index as the ratio of the normal luminance exiting from the window to that of a clear reference window with 100% transmittance. To be consistent with the ratings of the visible transmittance and solar heat gain coefficient, the luminance index is calculated when the window sees the full sky vault and the incident sun beam light is normal to its plane, that is when the window is in a horizontal position. At this position, the window luminance reaches the maximum value. Window luminance index calculated at other incidence angles and window positions are possible, particularly for window design consideration, but not needed for window product rating purposes.

The normal luminance exiting from the window under a given sky condition is expressed as follows:

$$L_{wn} = (1 - H_{f,t,n}) \cdot VT_{f,n} \cdot L_h + H_{f,t,n} \cdot VT_{f,n} \cdot E_{bh} / \pi + H_{f,t,d} \cdot VT_{f,d} \cdot E_{dh} / \pi + VR_{b,d} \cdot E_{i,dif} / \pi \quad (10)$$

The indoor illuminance level ($E_{i,dif}$) is usually constant since it is compounded of the amount of daylight admitted through the window and indoor artificial lighting (i.e, using proper daylight-linked controls). For

product rating purposes, we exclude the contribution of the indoor illuminance level (last term of equation 10) in the luminance rating. The window luminance index is thus expressed as follows:

$$LI = (1 - H_{f,t,n}) \cdot VT_{f,n} + \frac{E_{dh}}{\pi \cdot L_h} (H_{f,t,n} \cdot VT_{f,n} \cdot E_{bh}/E_{dh} + H_{f,t,d} \cdot VT_{f,d}) \quad (11)$$

Equation (11) stipulates that the luminance index depends on the normal and diffuse transmission haze and visible transmittance of the window, the ratio of the horizontal illuminance-to-luminance of the sky, and the ratio of the sunbeam-to-sky diffuse horizontal illuminance. The ratio of the sky horizontal illuminance-to-luminance (E_{dh}/L_h) is equal to 3.141, 2.445, 1.570 and 0.967 for uniform overcast, CIE standard overcast, IES partly cloudy and CIE standard clear sky conditions, respectively⁽¹¹⁾. The ratio of the horizontal sunbeam to sky diffuse illuminance (E_{bh}/E_{dh}) is equal to 0, 1.270 and 6.365 for overcast, IES partly cloudy and CIE standard clear sky conditions, respectively⁽¹¹⁾. By virtue of equation (11), the window luminance index of clear window products is equal to the visible transmittance ratings. For diffuse window products, the LI = 0.778, 1.134 and 2.27 times the visible transmittance ratings for the CIE standard overcast, IES partly cloudy and CIE standard clear sky conditions, respectively. These results shows that diffuse window products may result in higher potential glare problems, particularly under partly cloudy or clear sky condition than the regular clear window products. If one adopts the limiting luminance value of 2500 cd/m², which corresponds to the borderline between comfort and discomfort⁽⁷⁾, then the maximum threshold values of LI would be 0.29, 0.09, and 0.15 for CIE standard overcast, IES partly cloudy and CIE standard clear sky conditions, respectively. It should be noted that, however, the maximum values of LI may be higher as recent research⁽¹⁷⁾ on translucent windows showed that luminances in the order of 6000 cd/m² were not seriously problematic for perceived discomfort glare.

4.5 Light Diffusion Quality

Light diffusion quality of a fenestration product relates to the uniformity of illuminance on work planes. Uniformity of illuminance indicates the relative deviation of the minimum illuminance with respect to the average illuminance on a given plane. Uniformity of illuminance is an important requirement in lighting design. Non-uniformity of illuminance on a given plane may cause visual discomfort, reduce task performance and pose problems to the lighting control system and occupant safety. We characterize the light diffusion quality (LDQ) of a fenestration product by the total transmission haze index determined at a normal incidence angle ($H_{t,n}$). The transmission haze index applies well to glazing materials, which exhibit at most one specular peak luminance along the incidence direction of beam light. In other words, glazing materials, which exhibit multiple specular peak luminances off the incidence direction cannot be rated using the transmission haze index. For these materials, the bidirectional transmittance distribution function must be known. As by definition light diffusion excludes the peak luminances, we define the light diffusion quality (LDQ) at a normal incidence angle as follows:

$$LDQ = 1 - \frac{\int_{\Omega} L_{wp,n} \cdot \cos \theta \cdot d\omega}{\int_{\Omega} L_{w,n} \cdot \cos \theta \cdot d\omega} \quad (12)$$

where:

$L_{w,n}$: window luminance along the emerging direction (θ) for normal incident beam light (cd/m^2);

$L_{wp,n}$: window peak luminance along the emerging direction (θ) for normal incident beam light (cd/m^2);

ω : elemental solid angle (steradians); and

Ω : solid angle domain.

The window peak luminance is calculated with respect to a perfect diffusing material having the same light output energy as the material under consideration. This is given by the following relation:

$$L_{wp,n} = \begin{cases} L_{w,n}, & \text{if } L_{w,n} > E_{i,n} / \pi \cdot VT_{f,n} \\ 0, & \text{otherwise} \end{cases} \quad (13)$$

with $E_{i,n}$ is the incident illuminance received normal to the window plane. By introducing the bidirectional transmittance distribution function ($BTDF = L_{w,n} / E_{i,n}$), equation (12) reduces to the following:

$$LDQ = 1 - \frac{1}{VT_{f,n}} \int_{\Omega} BTDF \cdot \cos \theta \cdot d\omega, \text{ if } BTDF > VT_{f,n} / \pi \quad (14)$$

It should be noted that LDQ, given by equation (14), is equivalent to the transmission haze index for glazing materials with at most one specular peak luminance along the incidence direction.

5 Application

To demonstrate the new rating indices, typical complex window products found in buildings are considered: a diffuse window and clear window combined with an interior shading screen and in-between pane perforated Venetian blinds.

5.1 Diffuse Window

The diffuse window consists of a 6 mm double clear-over-white acrylic glazing. The optical properties of the clear acrylic sheet at a normal incidence angle are: transmittance = 0.92, and reflectance = 0.074, and those of the white sheet are: transmittance = 0.49, and reflectance = 0.30 (transmission haze = reflection haze = 1). The optical properties at oblique incidence angles are calculated using the laws of optics for the clear glazing, and considered constant for the white glazing. Table 1 presents the computed indices

of the diffuse window. Since the white acrylic glazing is fully diffuse, the window provides no outdoor or indoor view ($OVI = IVI = 0$). When compared with a clear window product with similar normal visible transmittance ($VT = 0.47$), the diffuse window may reduce its luminance by up to 28% under overcast sky conditions. Under clear sky conditions, however, the diffuse window may increase the luminance by more than 100%.

Table 1 Computed indices of a double clear-over-diffuse window

Visible Transmittance (VT)	Luminance Index (LI)		
	Overcast sky	Partly-cloudy sky	Clear sky
0.47	0.34	0.49	0.98

5.2 Clear Window with Interior Shading Screen

Two types of shading screens are considered: a light-coloured screen with reflectance of 0.80, and a dark-coloured screen with reflectance 0.10. The screen fibres are assumed opaque and diffuse with thickness (diameter) equal to 1 mm. The screen is placed at the interior side of the window. Table 2 presents the new indices for the clear window and screen system.

The results show that the dark-coloured screen does not significantly affect the outdoor view (almost full view) and indoor view index (no view during daytime, but full view during night time). The reason why the screened window provides no indoor view during daytime while providing full outdoor view is due to the fact that the veiling reflections from the exterior window surface to the observer's eye contributes to reduce the indoor view, particularly at high outdoor illuminance levels. Figure 2 shows some camera snapshots taken for a double clear window without and with an interior dark opaque shading screen under a sunny day. As expected, outdoor objects are clearly seen through the clear window whereas indoor objects cannot be seen from the outside due to veiling reflections, which project the outside image onto the window surface. Adding a dark opaque shading screen at the interior side of the window seems not to affect the outdoor view (image on the right). The luminance of the dark-coloured screened window is linearly proportional to the screen openness factor, that is, a 25% openness results in the reduction of about 75% of the window luminance compared to a non-screened window. The sky condition seems not to affect the window luminance.

However, the light-coloured screen may reduce the outdoor view by up to 25%. The window luminance significantly decreases with the openness factor of the screen. The sky condition has a great impact on the window luminance. At 25% openness, the window luminance is reduced by about 70% under

overcast sky conditions as compared with a non-screened window. Under clear sky conditions, the window luminance is increased by about 33% more than under overcast sky conditions.

Table 2 Computed indices of a double clear window with an interior shading screen

Light-coloured screen (reflectance = 0.80)								
Openness Factor (%)	Visible Trans. (VT)	Trans. Haze (H_t)	Luminance Index (LI)			Outdoor view Index (OVI)	Indoor view Index (IVI)	
			Overcast sky	Partly-cloudy sky	Clear sky		Daytime (clear sky)	Night time
100	0.78	0.00	0.78	0.78	0.78	1.00	0.14	1.00
25	0.21	0.08	0.24	0.25	0.32	0.75	0.00	0.92
5	0.04	0.05	0.05	0.05	0.06	0.83	0.00	0.90
Dark-coloured screen (reflectance = 0.10)								
25	0.20	0.00	0.20	0.20	0.20	0.98	0.01	1.00
5	0.04	0.00	0.04	0.04	0.04	1.00	0.00	1.00

View-out through a clear window

View-in through a clear window

View-out through a clear window with a dark screen (5% openness)

Figure 2 Effect of veiling specular reflection on the outdoor and indoor view through a clear window without and with a shading screen under a clear sunny day.

5.3 Clear Window with Integrated Perforated Venetian Blinds

Two types of Venetian blinds are considered, with light and dark coloured slat materials. The slats are opaque and assumed diffuse with the geometrical dimensions fixed at: thickness = 0.22 mm, width = spacing = 0.02 m, angle = 45° up, and perforation = 5% of slat surface. The Venetian blinds are placed between the glazing panes of the double clear window. Table 3 presents the calculated indices for the window and blind system. The results show that the dark coloured slats slightly affect the window

luminance (less than 4%), outdoor view (almost full view) and indoor view (no privacy during night time) as compared with a clear window with similar visible transmittance. However, light coloured slats may increase the window luminance by up to 50%, and reduce the outdoor view by up to 66% (during day time) and indoor view by up to 33% (during night time). This is due to the fact that light coloured slats increase light scattering by up to 36%, compared with the dark coloured slats (very weak scattering).

Table 3 Computed indices of a double clear window with in-between pane perforated Venetian blinds (slat angle 45° up)

Slat material	Visible Trans. (VT)	Trans. Haze (H _t)	Luminance Index (LI)			Outdoor view Index (OVI)	Indoor view Index (IVI)	
			overcast sky	partly-cloudy sky	clear sky		daytime (clear sky)	night time
Dark coloured	0.23	0.03	0.23	0.23	0.24	0.91	0.02	0.98
Light coloured	0.35	0.36	0.35	0.36	0.52	0.34	0.00	0.67

6 Conclusion

This paper set the theoretical development of new indices of merit to rate complex fenestration products for view through, luminance and light diffusion quality. These indices are expected to relate to the perceived building occupant satisfaction with regards to the outdoor view, privacy, discomfort glare and illuminance uniformity on work planes. The new indices along with those for energy performance (U-factor, solar heat gain coefficient) indicate the expected performance of the fenestration product after installation in real buildings with regards to energy and occupant satisfaction. Pre-selection of fenestration products prior to their installation based on the new indices may prevent building occupant dissatisfaction with regards to the indoor environmental conditions created by the installed product, and therefore avoid any otherwise possible detrimental impact on the energy performance of the product.

Application of the new indices to some typical complex window products, namely a double clear-over-diffuse window, a double clear window combined with an interior shading screen, and a double clear window combined with in-between pane Venetian perforated blinds, revealed the following findings:

- Clear window products offer full outdoor view. However, the indoor view is dependent on the indoor and outdoor illuminance levels. Under clear sky conditions during daytime with typical office indoor illuminances, double clear window products offer no indoor view due to the effect of

the veiling specular reflections from the exterior surface of the window to the outdoor observer's eye. Under night time conditions, the situation is reversed: full indoor view with no outdoor view.

- As expected, a double clear-over-diffuse window provides no outdoor or indoor view. When compared with a clear window product with the same visible transmittance, the diffuse window may reduce the luminance by up to 28% under overcast sky conditions and increase it by more than 100% under partly cloudy or clear sky conditions.
- A dark coloured interior screen of a double clear window does not affect the outdoor view. The window luminance is linearly proportional to the screen openness factor, and the sky condition does not significantly affect the window luminance index. However, the light coloured screen has a significant effect on the outdoor view, and window luminance indices. The screened window may reduce the outdoor view by up to 25%. The window luminance index significantly decreases with the openness factor of the screen and the sky condition has great effect on the window luminance index. For example, a screen with an openness factor of 25% reduces the window luminance by about 70% under overcast sky conditions as compared with a non screened window. Under clear sky conditions, the window luminance is increased by about 33% more than under overcast sky conditions.
- Clear windows with in-between pane perforated Venetian blinds slightly affect the window luminance, light forward scattering, and outdoor view, particularly with dark coloured slats, as compared with a clear window with similar visible transmittance. However, light coloured slats may increase the window luminance light forward scattering by up 50% and 36%, respectively, and reduce the outdoor view by up to 66% and indoor view by up to 33% (better privacy during night time).

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8 References

- 1 Keighley E.C. Visual Requirement and Reduced Fenestration in Office Buildings - a Study of Window Shape. Building Science. 1973; 8; 311-320.
- 2 Ne'eman E. and Hopkinson R.G. Critical minimum acceptable window Size: a study of Window Design and Provision of a View. Applied Ergonomics. 1971; 2 (4); 17-27.

- 3 Boyce P.R., Hunter C., and Howlett O. The benefits of daylight through windows. Lighting Research Center of the Rensselaer Polytechnic Institute; New York: USA; 2003.
- 4 Farley K.M.J. and Veitch J.A. A room with a view: A review of the effects of windows on work and wellbeing. IRC Research Report (IRC-RR-136). National Research Council Canada, Canada. 2001.
- 5 Mochizuki E. and Iwata T. Discomfort glare caused by a window screen with non-uniform luminance distribution. Proceedings of Lux Europa. September 2005a; Berlin, Germany; 1-4.
- 6 Mochizuki E. and Iwata T. Experimental study on the visibility of an outside view through a window screen. Proceedings of Lux Europa. September 2005b; Berlin, Germany; 162-164.
- 7 Fisekis K., Davies M., Kolokotroni M. and Langford P. Prediction of discomfort glare from windows. Lighting Research & Technology. 2003; 35(4); 360-371.
- 8 Boubekri M., and Boyer L.L. Effect of window size and sunlight presence on glare. Lighting Research & Technology. 1992; 24(2); 69-74.
- 9 Wienold J., and Christoffersen J. Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. Energy and Buildings. 2006; 38; 743-757.
- 10 NRCC. SkyVision (version 1.2), skylight performance assessment software. National Research Council of Canada. Web site: <http://irc.nrc-cnrc.gc.ca/ie/light/skyvision/>, accessed August 2005.
- 11 IESNA. Lighting Handbook, Reference And Application Volume. New York: Illuminating Engineering Society of North America, 2000.
- 12 Boyce P.R. Human factors in lighting. Lighting Research Center of the Rensselaer Polytechnic Institute; Taylor & Francis (2 Ed.); New York: USA; 2003.
- 13 CIE, Discomfort Glare in the Interior Working Environment. Publication CIE No. 55 (TC-3.4), International Commission on Illumination; France. 1983.
- 14 Boyce P.R. Lighting research for interiors: the beginning of the end or the end of the beginning. Lighting Research & Technology. 2004; 36(4); 283-294.
- 15 CIE. CIE collection on glare. International Commission on Illumination; Austria. 2002.
- 16 Kim W. and Koga Y. Glare constant G_w for the evaluation of discomfort glare from windows. Solar Energy. 2005; 78; 105-111.
- 17 Veitch J.A., Private communication. 2005.