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LIGHTING CHARACTERISTICS OF COMPLEX FENESTRATION SYSTEMS

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ABSTRACT

The need for energy conservation in buildings has spurred innovations in window technologies. These products include windows combined with shading devices, and windows featuring complex glazings such as smart glazings, translucent and transparent insulation, patterned or decorative glass. Unfortunately, little is known about their impact on the quality of the indoor environment. This paper addresses the development of new lighting quality indices for the outdoor view (which gives a feeling of connection to the outside), indoor view (which may affect feelings of privacy), and window luminance (which indicates the potential risk of discomfort glare). The new indices were applied to a typical fenestration system, consisting of a clear window equiped with an interior perforated shading screen with opaque and translucent materials. The simulation results indicate that the the light-coloured screen has a significant impact on the outdoor view and window's luminance, depending greatly on the sky conditions. Under clear sky conditions, the window's luminance may be increased by up to 80% compared with overcast sky conditions, particularly for a window with a translucent screen.

INTRODUCTION

The need for energy conservation and better indoor environment quality in buildings has spurred innovations in window technologies. Complex fenestration systems refer to any window product that incorporates a non-clear (non-specular) layer in the glazing assembly or in its attachments (or shadings). Window component manufacturers have responded to the actual requirements with superior products that combine the established technologies of the advanced window products (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.

Complex fenestration systems (CFS) have usually superior energy performance (e.g., lower thermal transmittance or annual energy performance), but may have a profound effect on the indoor environment as experienced by occupants, by impairing the view to outside/inside and increasing the potential risk of glare. Good view and glare-free environment are not only important for the building's occupant satisfaction and organizational productivity, but also for the fenestration product commercialization. Fenestration products that have negative effects on the indoor environment can expect reduced market penetration and lower sales.

There are a few studies related the indoor environment quality (IEQ) performance of complex fenestration systems. Iwata and Mochizuki (2005) and Mochizuki and Iwata (2005a, 2005b) conducted physical and human subject measurements to evaluate the optical properties, discomfort glare and visibility of a screen window. Recently, Laouadi and Parekh (2005) developed a detailed optical model for complex fenestration systems and derived new lighting quality metrics for product rating purposes. The aim of this paper is to apply the new lighting quality indices on a typical complex fenestration system consisting of a double clear window combined with various types of an interior perforated shading screen.

Optical Model of CFS

The details of the optical model of complex fenestration systems may be found in Laouadi and Parekh (2005). The model is implemented in a new version of SkyVision (NRCC, 2005), which will be released in the upcoming years. The model is 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 radiation energy, respectively. The forward (backward) haze is defined as the ratio of the scattered portion of the transmitted (reflected) energy around the specular (mirror) direction to the total transmitted (reflected) energy (ASTM, 2000). The transmission (forward) haze property of a transparent medium indicates the contrast of objects when viewed through it. The reflection (backward) haze property indicates the gloss of materials when illuminated at a given direction. The gloss index is a measure of the relative specular reflectance with respect to a reference material with 100 % gloss (ASTM, 1989). The higher the reflection haze, the lower the gloss. The transmission haze can be measured using exiting standards such as the ASTM D1003-00 (ASTM, 2000) for haze values lower than 30%, or ASTM 167-96 (ASTM, 1996) for higher haze values. The ASTM standard D523-89 (ASTM, 1989) is used to measure the gloss index.

Lighting Quality Indices of CFS

Complex fenestration systems affect the lighting quality in two ways: they may impair the view through the window due to light scattering, and modify the luminance of the window when compared with a clear window product with similar optical properties (transmittance, reflectance). The previously mentioned optical model of CFS is used to derive new indices for the window luminance and the view impairment.

Luminance Index

The window luminance is an important factor for discomfort glare calculation (IESNA, 2000; CIE, 2002). Discomfort glare does not only affects the building occupant satisfaction, performance and health (Boyce, 2004; Boyce, 2003), but also the energy performance of the window product. For example, reducing the potential for glare may result in the reduction of daylight and solar heat gains, which may therefore result in increasing seasonal building energy use.

Previous studies (Kim and Koga, 2005; Fisekis et al., 2003) showed that the discomfort glare rating is proportional to the luminance (or intensity) of the window. For clear window products, where the radiation direction of the outdoor light sources is not altered after transmission, the window luminance becomes dependent on the luminance of the outdoor sources and the window transmittance. For fully diffuse window products where the radiation direction of the source is altered after transmission, the window luminance, however, becomes dependent on the amount of light falling on it. In this case, the window may increase or reduce the luminance along the line of view to the outdoor source. 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 or scattered 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 design and product rating purposes, we exclude the sunbeam light in the beam luminance component as the sun source subtends a very small angle (0.5^{o}) 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 horizontal luminance of a given window product to that of a clear reference window product with 100% transmittance. The window horizontal luminance under a given sky condition is expressed as follows (neglecting the contribution of the indoor background luminance).

$$L_w = \left(1 - H_{f,t,n}\right) \cdot VT_{f,n} \cdot L_h + H_{f,t,n} \cdot VT_{f,n} \cdot E_{bh} / \pi + H_{f,t,d} \cdot VT_{f,d} \cdot E_{dh} / \pi \qquad (1)$$

where:

E_{bh} : horizontal sunbeam illuminance received normal to the window surface;

E_{dh} : horizontal diffuse illuminance under a given sky condition;

L_w : window horizontal luminance;

L_h : sky horizontal (or zenith) luminance, excluding sunbeam light;

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

$H_{f,t,d}$: window hemispherical transmission haze for diffuse radiation incident on the front window surface;

$VT_{f,n}$: window visible transmittance for normal beam radiation incident on the front window surface; and

$VT_{f,d}$: window hemispherical visible transmittance for diffuse radiation incident on the front window surface.

The window luminance index is thus expressed as follows:

$$LI = \left(1 - H_{f,t,n}\right) \cdot VT_{f,n} + \frac{E_{dh}}{\pi \cdot L_h}\left(H_{f,t,n} \cdot VT_{f,n} \cdot E_{bh} / E_{dh} + H_{f,t,d} \cdot VT_{f,d}\right) \qquad (2)$$

Equation (2) stipulates that the luminance index depends on the normal and hemispherical 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 (IESNA, 2000). 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

(IESNA, 2000). By virtue of equation (2), the window luminance index of clear window products is equal to the visible transmittance (VT). For diffuse window products, the LI = 0.778, 1.134 and 2.27 times the visible transmittance 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 conditions than the regular clear window products. Recent research (Veitch, 2005) showed that translucent windows were subject to very high luminances when compared with a regular clear window with interior perforated screen shading, particularly when the direct sunlight hits the window surface. However, there was little evidence that these very high luminances were seriously problematic for discomfort glare.

View impairment index

The human visual system distinguishes objects through their luminance contrast and color difference with respect to their background (IESNA, 2000). The luminance contrast indicates the relative difference between the luminance of the object and its 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 (Boyce, 2003). 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 perturbation to the view of objects through the scattering of the incoming light 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 scattered and specular veiling luminance to the total luminance exiting from the window towards the observer's eye:

$$VRI(\nu) = \frac{L_{obj}(\nu) \cdot VT_f(\nu) \cdot H_{f,t}(\nu) + L_{b,sc} + L_{b,veil,dif} + L_{b,veil}(\nu, \theta_l)}{L_{obj}(\nu) \cdot VT_f(\nu) + L_{b,sc} + L_{b,veil,dif} + L_{b,veil}(\nu, \theta_s)} \quad (3)$$

where:

$H_{f,t}$: transmission haze of the window along a given view line direction for visible radiation incident on the front (exterior) window surface;

L_{obj} : luminance of the target object seen through a window along a given view line direction;

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

$L_{b,veil}$: veiling specular luminance from the beam light source reflecting from the back (interior) surface of the window;

$L_{b,veil,dif}$: veiling specular luminance from diffuse background lighting;

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

VT_f : visible transmittance of the window along a given view line direction for radiation incident on the front (exterior) window surface;

ν : view angle with respect to the window surface normal;

θ_l : incidence angle of the light source; and

θ_s : incidence angle of sunbeam light.

By considering Figure 1, the scattered and veiling luminances are expressed as follows:

$$L_{b,sc} = \begin{bmatrix} E_{sun} \cdot \cos(\theta_s) \cdot VT_f(\theta_s) \cdot H_{f,t}(\theta_s) + \\ E_{e,dif} \cdot VT_{f,d} \cdot H_{f,t,d} + E_{i,dif} \cdot VR_{b,d} \cdot H_{b,r,d} + \\ L_s \cdot \Omega_s \cdot \cos(\theta_l) \cdot VR_b(\theta_l) \cdot H_{b,r}(\theta_l) \end{bmatrix} / \pi \quad (4)$$

$$L_{b,veil}(\nu, \theta_l) = \begin{cases} 0, \text{ if view angle } (\nu) = \text{reflection angle } (\theta_l) \\ L_s(\theta_l) \cdot VR_b(\theta_l) \cdot [1 - H_{b,r}(\theta_l)] \quad \text{otherwise} \end{cases} \quad (5)$$

$$L_{b,veil,dif} = E_{i,dif} / \pi \cdot VR_b(\nu) \cdot [1 - H_{b,r}(\nu)] \quad (6)$$

where:

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

$H_{b,r,d}$: diffuse reflection haze for the incident diffuse radiation on the back (interior) window surface;
L_s : luminance of the light source along a given incidence direction;
$E_{e,dif}$: diffuse exterior illuminance from the sky and ground received at the front surface of the window;
$E_{i,dif}$: diffuse interior illuminance from the surrounding background received at the back surface of the window;
E_{sun} : normal illuminance of the sunbeam light;
VR_b : visible reflectance of the window along a given direction of radiation incident on the back window surface;
$VR_{b,d}$: visible diffuse reflectance of the back window surface; and
Ω_s : solid angle that subtends the light source seen from the window surface.

Equation (3) 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 haze H = 1 fully impair the view, irrespective of the surrounding lighting conditions (VRI = 1). The view of objects seen through a clear window (H = 0) depends, however, on the surrounding lighting conditions.

Outdoor View Index

Outdoor view is desirable in both residential and commercial buildings. Some previous research has also shown that the outdoor view may positively affect the wellbeing and health of building-occupants (Boyce et al., 2003; Farley and Veitch, 2001). There are a number of factors that may influence the outdoor view, namely the optical characteristics and color of the window glazing product, the size and shape of the window opening (Keighley, 1973; Ne'eman and Hopkinson, 1971), 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. 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 the glazing material causing light scattering should be lower than the visual size threshold of the visual system. In addition, the luminance of the target object after exiting from the window to the observer's eye should be sufficiently larger 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 purely objective meaning. The subjective evaluation of the quality of view 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:

$$OVI_n = 1 - VRI_n \tag{7}$$

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

$$OVI_d = 1 - VRI_d \tag{8}$$

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

$$VRI_d = \frac{1}{VT_{f,d}} \int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi/2} VRI(\theta,\varphi) \cdot VT_f(\theta,\varphi) \cdot \sin 2\theta \cdot d\theta \cdot d\varphi \tag{9}$$

where:
OVI_n : normal outdoor view index;
OVI_d : average outdoor view index;
φ : azimuth angle of the incident radiation on the window surface;
θ : incidence angle of radiation.

Since the luminance of outdoor objects is usually not known at the design phase, 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:

$$VRI_n = \frac{VT_{f,n} \cdot H_{f,t,n} \cdot (\pi + E_{bh}/L_h) + E_{dh}/L_h \cdot VT_{f,d} \cdot H_{f,t,d}}{VT_{f,n} \cdot (\pi + E_{bh}/L_h \cdot H_{f,t,n}) + E_{dh}/L_h \cdot VT_{f,d} \cdot H_{f,t,d}} \tag{10}$$

where 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.

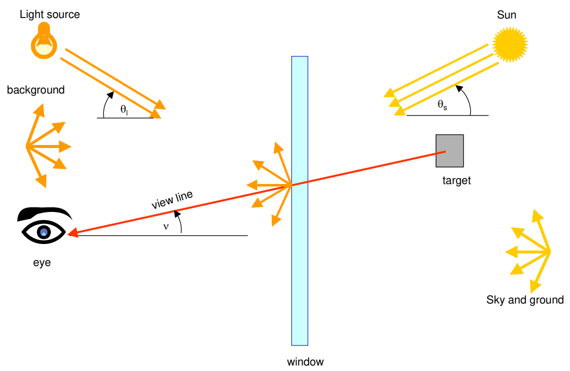

Figure 1. Factors affecting the view of objects seen through a window

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 worse 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. Light levels inside and outside 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 light levels. The indoor view index (IVI) is expressed by the same relations as the outdoor view index (equations 7 to 9), but with accounting for the indoor light levels. For engineering design and 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 light levels are that of standard sky conditions and sunlight parallel to the view line. In this case, the normal view impairment index takes the following form:

$$VRI_n = \frac{\left\{\begin{array}{l} VT_{b,n} \cdot H_{b,t,n} + E_{bh}/E_{i,dif} \cdot VR_{f,n} \cdot H_{f,r,n} + \\ E_{dh}/E_{i,dif} \cdot \left\{VR_{f,n} \cdot \left[1 - H_{f,r,n}\right] + VR_{f,d} \cdot H_{f,r,d}\right\} \end{array}\right\}}{\left\{\begin{array}{l} VT_{b,n} + E_{bh}/E_{i,dif} \cdot VR_{f,n} \cdot H_{f,r,n} + \\ E_{dh}/E_{i,dif} \cdot \left\{VR_{f,n} \cdot \left[1 - H_{f,r,n}\right] + VR_{f,d} \cdot H_{f,r,d}\right\} \end{array}\right\}} \quad (11)$$

Equation (11) 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 → 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 → 1). For equal indoor and outdoor light levels such as the case of 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 light levels.

APPLICATION

A typical window system consisting of a double 6 mm clear glass window equipped with an interior shading screen is used as an application to demonstrate the use of the new indices. Four types of shading screens are considered, representing combinations of translucent and opaque materials with light and dark colors. The transmittance of the translucent shading material (fiber or yarn material) is fixed at 0.15. The reflectance of the light and dark color screen materials are fixed at 0.70, and 0.1, respectively. All screen types have a thickness of 1 mm. Details on the optical model of a screen-like glazing may be found in Laouadi and Parekh (2005).

Figure 2 shows some snapshots of the view through a clear window alone and a clear window with an interior screen. The clear window alone provides a full view to the outside. However, the indoor view is fully impaired due to high outdoor light levels and the veiling reflection from the outside surface of the window. The clear window with the interior opaque dark screen (openness factor = 0.05) also provides a full view to the outside.

Table 1 presents the new indices of the window with a close-weave screen (openness factor = 0.15). Screens with opaque yarns do not significantly affect the window luminance when compared with a clear window with a similar normal transmittance. Opaque screens also provide almost full outdoor view and indoor view during night times, particularly for screens with dark colors. The screen color may reduce the outdoor view by about 17%, and the indoor view (during night times) by about 12%, and increase the luminance by about 20%. However, screens with translucent materials may significantly alter the view and luminance of the window, depending primarily on the outdoor and indoor lighting levels. Screens with translucent materials may increase the window luminance by up to 67% compared to a clear window with similar normal transmittance, particularly under clear sky conditions. The outdoor view may be reduced by up to 66% and 78% under overcast and clear sky conditions, respectively. The indoor view (during night times) may be reduced by up to 50%. The screen material color (or reflectance) slightly affects the view and window luminance (error less than 10%).

Figure 3 shows the effect of the screen openness factor on the outdoor view and luminance indices. Opaque dark screens provide full outdoor view, irrespective of the screen openness factor. For light-colored screens (with material reflectance = 0.7), the maximum reduction of the outdoor view occurs at an openness factor around 0.35, which results in the outdoor view index = 0.78. However, for screens with translucent materials, the outdoor view index increases with the openness factor. The screen material color (reflectance) may reduce the outdoor view by up to 15%. The luminance of the screened window increases with the openness factor and material reflectance of the screen. The screen material reflectance may increase the window luminance by up to 35% and 30% for opaque and translucent screens, respectively.

CONCLUSION

This paper addressed the development and application of new indices to characterize the lighting quality for the view and luminance of complex fenestration systems. These indices are important for building occupant satisfaction and organizational productivity. We hope that in the future these indices will part of the fenestration product ratings for indoor environment quality.

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Table 1. Lighting quality indices of double clear window with interior close-weave screens (openness factor = 0.15)

Window Screen Type ↓	Visible Transmittance (VT)	Luminance Index (LI)		Outdoor view Index (OVI) 0 → no view 1 → full view		Indoor view Index (IVI) 0 → no view 1 → full view
		Overcast sky	Clear sky	Overcast sky	Clear sky	Night time (Indoor illuminance = 500 lux)
Translucent dark	0.22	0.19	0.35	0.40	0.26	0.57
Translucent white	0.24	0.22	0.40	0.34	0.22	0.51
Opaque dark	0.12	0.12	0.12	0.99	0.99	0.99
Opaque white	0.12	0.14	0.14	0.83	0.82	0.92

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 under a clear sunny day. Objects outside the window are clearly seen through the window whereas indoor objects cannot be seen from the outside due the projection of the outside image on window surface. Outdoor objects are clear as viewed through the screened clear window.

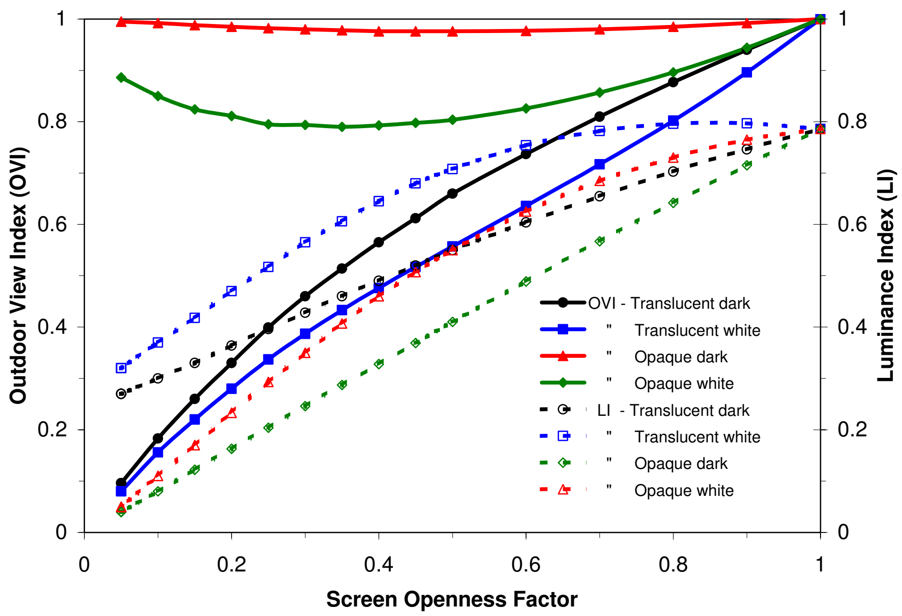

Figure 3 Effect of the screen openness factor on the outdoor view and luminance indices