# Selecting Roller Shades Properties Based on Glare Mitigation, Energy Performance and Connection to the Outdoors

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## Abstract

Visual comfort is one of the main priorities in designing working and living environments. Several indicators have been developed to quantify the degree of visual discomfort; however, there is a lack of studies in spaces with roller shades on the windows, commonly used in North America. Roller shades transmit direct and diffuse daylight and therefore their effect on visual comfort is complex. A recent study with human subjects proposed two alternative approaches in quantifying visual discomfort for the case of roller shades, based on (i) a modification of the Daylight Glare Probability (DGP) and (ii) an index based on the direct and the total portion of vertical illuminance on the eye of the observer. This paper uses a methodology based on the newly developed indices in an inverse way in order to propose suitable ranges for optical properties of the shade fabrics, in terms of openness factor and visible transmittance. A complex fenestration model that calculates the angular beam–beam and beam–diffuse shading optical properties is implemented within an advanced hybrid ray-tracing and radiosity daylighting model. Then, the concepts of annual discomfort frequency (Chan et al., 2015) and View Clarity Index (Konstantzos et al., 2015b) are used as a basis for the extraction of ranges of shade optical properties with respect to glare mitigation, energy performance and connection to the outdoors, for different sets of input parameters (location, orientation, glazing visible transmittance and distance from the window). The use of these extracted ranges can help architects select the most suitable shading products for their designs, minimizing glare complaints with the minimum cost in terms of lighting energy use and connection to the outdoors.

## 1. Introduction – Literature Review

Roller shades are an efficient and widely used shading approach, especially in perimeter office spaces; they combine solar and visual protection with aesthetically appealing presence. The selection of their properties can affect all three important aspects of the visual environment; visual comfort, in terms of mitigating glare, energy potential, by means of reducing required lighting energy, and connection to the outdoors.

There have been quite a few studies associating the fabric properties with energy performance, especially when combined with efficient shading control algorithms (Tzempelikos and Athienitis, 2007; Shen and Tzempelikos, 2012). However fewer studies take into account the important factor of visual comfort (Konstantzos et al., 2015a; Chan et al., 2014; Atzeri et al., 2014; Chan et al., 2015,). The latter paper proposed a systematic method of selecting appropriate shading properties towards mitigation of glare and increase of energy performance. For the investigation of glare, based on concerns expressed in a study by Konstantzos et al. (2015a) about potential inconsistencies of Daylight Glare Probability – DGP (Wienold and Christoffersen, 2006) when used in cases of facing the sun through fully applied shading fabrics, used a reasonable approach of a double illuminance criterion; using a threshold for the direct part of vertical illuminance to account for annual hours with the sun in the field of view and a threshold for the total vertical illuminance for the rest of the annual hours. In a recent study, Konstantzos and Tzempelikos (2016a) conducted an experiment with human subjects to evaluate the applicability of such a double criterion, and proposed two new discomfort indices, one luminance-based and one illuminance-based, to be used when the sun is visible

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through shading fabrics. Konstantzos et al. (2015b) investigated the impact of fabric properties in the clarity of view, shedding light on the connection to the outdoors with roller shades and introduced the View Clarity Index, a quantification of clarity based on the two most commonly available fabric properties, openness factor and visible transmittance.

This paper will propose a methodology to select suitable ranges for the optical properties of shading fabrics in terms of openness factor and visible transmittance with respect to glare mitigation, energy performance, and connection to the outdoors, using the newly proposed GlareEV and VCI indices to assess visual comfort and connection to the exterior respectively.

## 2. Methodology

### 2.1 Optical Properties of Roller Shades

Shading fabrics are characterized by a set of properties that identify their color and optical characteristics. That includes the openness factor (OF), the visible transmittance (TV) and the front and back reflectivities (RV). Among these, the ones that are primarily connected with the visual environment are the openness factor and the visible transmittance.

The openness factor reflects the weave density of the fabric and is an indication of the direct light being transmitted within it. Openness factors theoretically range from 0 (translucent fabrics) to 20 %, however most widely used fabrics are ranging from 1 % to 7 %, as higher values are often associated with conditions of visual discomfort and disability glare, while lower values have a negative impact on the outside view.

The visible transmittance reflects the total portion of illuminance transmitted through the fabric and is also an indirect indicator of the fabric's color; light-colored fabrics have higher Tv compared to darker fabrics of the same openness factor due to the additional allowed direct-to-diffuse light transmission.

The two aforementioned optical properties are commonly available by the fabrics' manufacturers, and their impact is highly dependent on the incidence angle of the incident light transmitted through the window.

### 2.2 A Suite of Metrics to Assess the Visual Environment

A strategy of maximizing lighting energy performance and connection to the outdoors while keeping visual comfort as a constraint constitutes a straightforward decision making process, which can be used either in existing buildings, in terms of retrofitting, or to optimize the design of new spaces, in terms of orientations, façade configurations, control methods or even spatial layouts according to the specific needs and functions of the space. The above can be all linked in one main annual metric, the Visual Environment Index (Konstantzos and Tzempelikos, 2016b), which consists of three parts: VEIc, related to visual comfort, VEIe, focusing on lighting energy performance and VEIv covering the connection to the outdoors (outside view). In this study, the same principles are used to propose a method of selecting optimal fabric properties for a given space.

The Visual Comfort Autonomy or VCA is defined as the portion of annual working hours when a person in a specific position and under a selected viewing direction is under visually comfortable conditions. VCA is a framework to evaluate discomfort, and can use any fitting discomfort index on a case-specific basis. For the needs of this study, where the shading fabrics are considered to be fully applied, the newly proposed discomfort index GlareEv (Konstantzos and Tzempelikos, 2016a) is used for the instances where the sun is within the field of view (Eq. 1), while a threshold for DGPs (Wienold, 2007) of 0.35, essentially associated with a 2760 lux threshold for the total vertical illuminance, is applied for all other cases.

$$Glare_{Ev} = 0.13 \cdot E_{v,dir(sun)}^{0.27} + 0.04 \cdot \left( \frac{E_v}{E_{v,dir(sun)}} \right)^{0.84} - 0.48 \quad (1)$$

$$\begin{cases} GlareEv < 0.41, \; sun \in FOV \\ DGPs < 0.35, \; sun \notin FOV \end{cases} \quad (2)$$

$$DGPs = 6.22 \times 10^{-5} \times E_V + 0.184 \quad (3)$$

where $E_{v,dir(sun)}$ is the direct vertical illuminance from the sun in the field of View and $E_v$ is the total vertical illuminance on the eye level. GlareEV is preferred over other luminance-based metrics as, due to its illuminance-based nature, it involves simpler calculations and faster simulations compared to more accurate metrics as DGPmod that require the calculation of detailed luminance mappings for each time step.

In order to comply with the VCA restrictions and constitute a space as comfortable, and also based on the study of Chan et al. (2015), there are two approaches to consider; (i) a reasonable standard of accepting a total of 5 % of annual working hours to be associated with discomfort (equivalent to VCA≥0.95) and (ii) a stricter consideration, of maintaining comfortable conditions for the entire working time of the year (equivalent to VCA=1). In lack of related literature focused on annual human subjects studies, it is unclear which of the two better complies with everyday practice; as visual discomfort does not occur in a transient form, it is important to eliminate every possible instance of discomfort in order to design glare-free indoor environments. Therefore, in this study only the safest approach (VCA=1) will be investigated, targeting to eliminate every single instance of glare. It can be inferred by reason that more flexible considerations might be also feasible, and the extent to which a space is protected from discomfort glare can be a decision of the architect, depending also on the operational objective of a space.

To account for the connection to the outdoors, the recently proposed View Clarity Index (Konstantzos et al., 2015b) is utilized (Eq. 4), associating the clarity of view with the openness factor and visible transmittance of the applied fabric.

$$VCI = 1.43 \cdot (OF)^{0.48} + 0.64 \cdot \left(\frac{OF}{T_v}\right)^{1.1} - 0.22 \qquad (4)$$

The latter was extracted in a human subjects study using a diverse questionnaire, defining clarity through various aspects (subjective and objective questions about visual acuity, color perception, distinguishability of given targets e.a.), and associates the clarity of view with the two most commonly available optical properties.

For the consideration of the energy performance, the continuous Daylight Autonomy (cDA) is used (Rogers, 2006). The latter index is mostly efficient for cases of light dimming, which is becoming a standard in green building, and gives partial credit for the times in which daylight illuminance is below the level of 300 lux, in order to comply with the IES standard LM-83-12 (IESNA, 2012).

## 2.3 Method Description

The proposed method targets to recommend fabric properties to be used in perimeter office spaces with respect to visual comfort, connection to the exterior, and lighting energy performance.

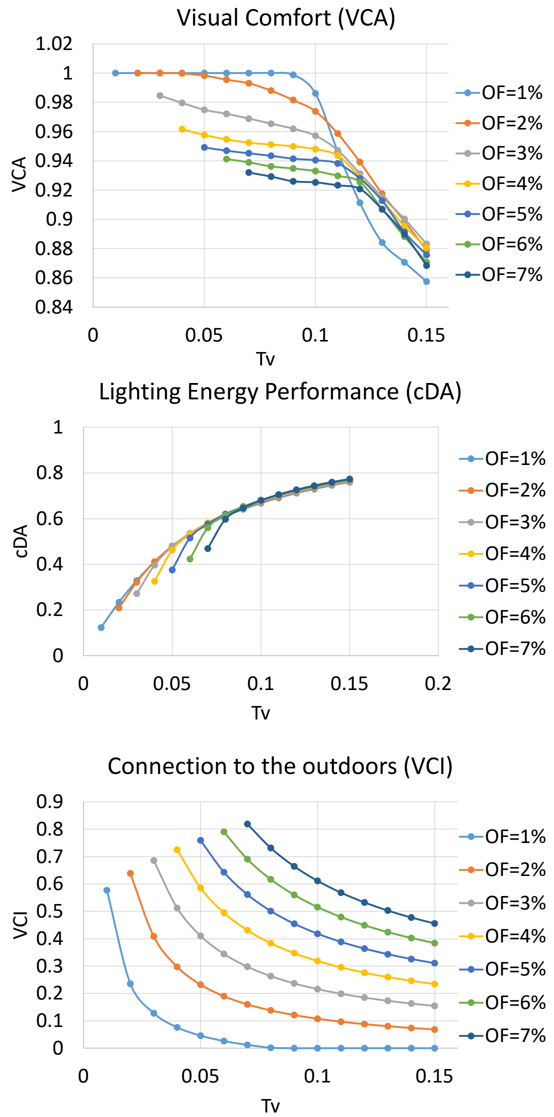


Fig. 1 – Impact of fabric properties on the three main factors of the visual environment; examples for south orientation and 1.75 m distance from window.

Among these goals, visual comfort is considered to be the most important, as discomfort can have negative effects, ranging from slight decrease in performance to serious disability of performing office work. Therefore, in the proposed method, visual comfort is used as a constraint, using the strict approach presented in 2.1 for the total elimination of discomfort instances. The use of VCA as a constraint gives acceptable ranges of fabrics, in terms of openness factor and visible transmittance.

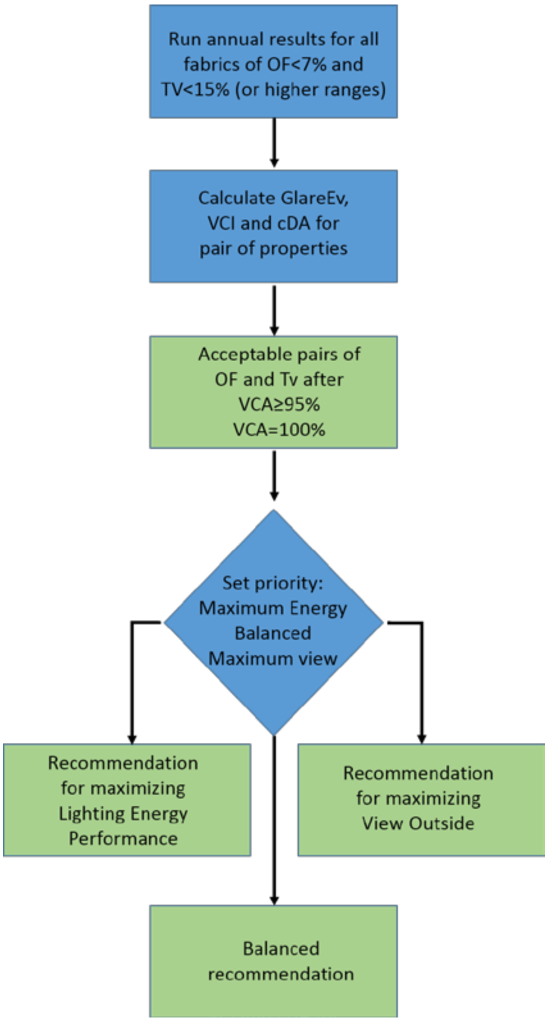


Fig. 2 – Proposed method flow-chart

However, lighting energy performance and connection to the outdoors are two contradicting objectives; lighting energy performance is by definition higher with increasing visible transmittance (portion of transmitted light through the fabric), while connection to the outdoors is negatively affected by the same increase (Konstantzos et al., 2015b). Therefore, in this study, three main different approaches are being presented when it comes to the two secondary objectives (view and lighting energy performance); proposing the optimal fabrics for (i) maximizing view, (ii) maximizing energy performance, and (iii) provide a balanced result of the two. Fig. 1 shows the impact of the fabric properties on the three main factors of the visual environment, while Fig. 2 shows a comprehensive flow chart of the proposed methodology.

While the cases of maximizing energy or view can be straightforward, the weighting of the two attributes for the balanced case cannot be conclusively decided due to the difference in nature of the two parameters. Therefore, and until more light is shed on that matter, for this study, two different objectives will be used to extract the optimal results for the balanced case: (i) a criterion of having the two attributes equally weighted (Bal.EW), which will at times compromise both view and energy performance to very low values and (ii) a flexible criterion (Bal.FL) which will first require each of the attributes to be over a minimum value of 0.25, and then search for the pair which will lead to the two attributes as much equally weighted as possible given that none of the two would get very low values. The objective for the balanced approach is shown in Equations 5 and 6, as the pair of points with the minimum distance from the dichotomous line of the Cartesian system without or with the minimum restrictions respectively.

$$\min\left(\frac{VCI_i - cDA_i}{\sqrt{2}}\right) \tag{5}$$

$$\min\left(\frac{VCI_i - cDA_i}{\sqrt{2}}\right),\ with\ VCI_i, cDA_i \geq 0.25 \tag{6}$$

The authors believe that a compromise of the connection to the outside would affect the perception of daylight in the space, so it shouldn't be underestimated. A sample Pareto front chart of the four decision making approaches can be seen in Fig. 3; the points of the graph represent the combinations of OF and Tv that are eligible for use after the VCA≥95 % restriction, the green point is the optimal fabric to maximize view (OF=4 %-Tv=4 %), the yellow point the optimal fabric to maximize lighting energy performance (OF=2 %-Tv=11 %), the red point reflects the equally weighted balance of the two attributes (here fabric OF=1 % and Tv=2 %), and the black point shows the flexible balance (here OF=4 %-Tv=6 %).

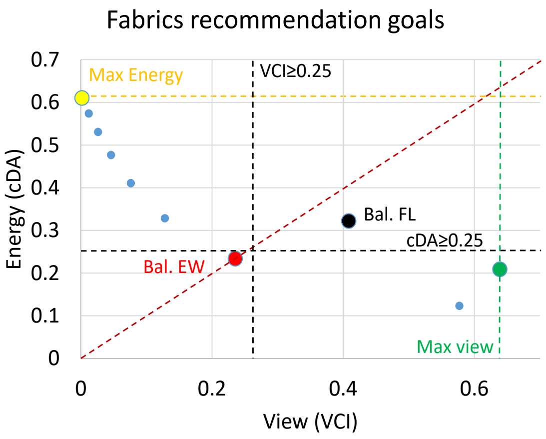


Fig. 3 – Pareto Front chart showing the logic of optimal pairs selection – results for south orientation, 1.75 m from the window and the strict VCA restriction (VCA=1)

## 2.4 Modeling Methodology

A hybrid ray-tracing and radiosity daylighting model with a glare module is used for the calculations of VCA and continuous daylight autonomy for the suggested configurations. The model consists of four main parts, the first simulating the exterior lighting conditions (direct and diffuse illuminance on the exterior of the window), based on TMY3 weather files, the second simulating the properties of the complex fenestration system (glazing and dynamic shading), the third calculating the interior mapping for luminances and illuminances over a specified grid, and the fourth finally calculating the glare index for each position and viewing direction of interest. We use the model by Perez et al. (1987) to calculate the diffuse sky illuminance distribution. For the interior illuminance and luminance distributions calculations, the hybrid ray tracing and radiosity module (Chan and Tzempelikos, 2012) was implemented. Ray tracing is used to capture the sun's position and the directly lit areas in the interior. Then, the radiosity method uses the initial exitances obtained above to apply the inter-reflections of the interior surfaces and calculate the final luminance and illuminance distribution in the interior for the desired grid of positions, while all surfaces densely discretized in order for the glare module to accurately identify the glare sources which will be taken into account in the equations. The model has been validated with experiments (Chan et al, 2014). The detailed beam-diffuse and off-normal properties of the roller shades were calculated using the semi- empirical method introduced by Kotey et al. (2009). This model, which proved to be accurate and reliable for several types of standard (PVC-coated and vinyl) fabrics, calculates the beam-beam and beam-total visible transmittance angular variation as a function of the incidence angle and the normal OF and Tv properties, provided by manufacturers. The latest version of EnergyPlus (2015) includes this angular model in the "window thermal calculation module", as part of the new "equivalent layer fenestration model". In summary, the angular beam-beam shade transmittance ($\tau_{bb}$) is calculated from:

$$\tau_{bb}(\theta)=\tau_{bb}(0)\times\left(\cos\left(\frac{\pi}{2}\times\frac{\theta}{\theta_{cut-off}}\right)\right)^{b} \qquad (6)$$

where θ is the solar incidence angle, $\tau_{bb}(0)$ is the beam-beam transmittance at normal incidence, assumed equal to the OF of the fabric (provided by manufacturers), and b and $\theta_{cut-off}$ are parameters that depend on $\tau_{bb}(0)$, as explained in Kotey et al. (2009). The angular beam-total transmittance ($\tau_{bt}$) is calculated from:

$$\tau_{bt}(\theta)=\tau_{bt}(0)\times(\cos\theta)^{d},\{\theta<\theta_{cut-off}\} \qquad (7)$$

where $\tau_{bt}$ (0) is the beam-total transmittance at normal incidence (total visible transmittance provided by manufacturers) and d is a parameter that depends on openness factor and total visible transmittance. The cut-off angle should not be applied to light-colored fabrics, to account for direct light scattering at higher angles, while small corrections might be needed for dark-colored fabrics (Tzempelikos and Chan, 2016). The beam-diffuse transmittance, necessary for the accurate modeling of light transfer through shades, is then equal to $\tau_{bt}$ -$\tau_{bb}$ for each angle. Finally, integrating $\tau_{bt}$ over the hemisphere yields the diffuse-diffuse shade transmittance ($\tau_{dd}$), which cannot be measured or calculated otherwise.

As a geometry for the current study, a private office space is selected with a floorplan of 5mx5m and height of 3.4m with a 70 % WWR. Also, a standard double clear glazing system is used, to be compatible with most existing perimeter office spaces. The results are presented for two different distances from the window (0.75 m, 1.75 m) and for the four main orientations (S,W,E,N). The location of the simulations was chosen to be Lafayette, IN.

## 3. Results - Discussion

Table 1 shows the allowed combinations of fabric properties based only on visual comfort, for a viewing distance of 1.75 m from the window. The number in brackets characterizes the maximum permitted visible transmittance (Tv) for the given openness factor.

Table 1 – Allowed fabric combinations for 1.75 m (VCA=1)

| | |
|---|---|
| S | 1 % (8 %), 2 % (3 %) |
| W | 1 % (8 %), 2 % (3 %) |
| E | 1 % (10 %), 2 % (8 %) |
| N | No restriction |

The above permitted combinations can be used in order to comply with the visual comfort constraint. However, in order to take advantage of the full potential in terms of lighting energy performance, outside view or a balanced combination of the two, the method presented in 2.3 can propose the optimal pairs for each case. These can be seen in Table 2:

Table 2 – Fabric recommendations for 1.75 m (VCA=1)

| | View | Energy | Bal. EW | Bal. FL |
|---|---|---|---|---|
| S | 2%-2% | 1%-8% | 1%-2% | 2%-3% |
| W | 2%-2% | 1%-8% | 1%-2% | 2%-3% |
| E | 2%-2% | 1%-10% | 2%-4% | 2%-4% |
| N | N/A | N/A | N/A | N/A |

In cases where the immediate area near the window needs to host occupants, the results are modified as seen in Tables 3 and 4. Due to the poor sunlight exposure of northern facades in the northern hemisphere, no recommendations are stated for this orientation, as all fabrics in the evaluated range meet the strict VCA criterion of zero glare hours.

It can be derived by the results that the impact of the direct-to-direct and direct-to-diffuse portion of the fabrics, depending on their properties, can affect the results in different ways for different objectives; to maximize the clarity of view, the objective is to achieve an openness factor close to the visible transmittance, in order to minimize the direct-to-diffuse portion of the light transmission. The latter however is essential to increase the lighting energy performance of the space by maximizing daylight illuminance. Therefore, when focused on energy performance, the objective is for a given openness factor to use the maximum permitted visible transmittance.

Table 3 – Allowed fabric combinations for 0.75 m (VCA=1)

| | |
|---|---|
| S | 1 % (5 %), 2 % (2 %) |
| W | 1 % (5 %), 2 % (2 %) |
| E | 1 % (6 %), 2 % (6 %) |
| N | No restriction |

Table 4 – Fabric recommendations for 0.75 m (VCA=1)

| | View | Energy | Bal. EW | Bal. FL |
|---|---|---|---|---|
| S | 2%-2% | 1%-5% | 1%-2% | 2%-2% |
| W | 2%-2% | 1%-5% | 1%-2% | 2%-2% |
| E | 2%-2% | 2%-6% | 1%-2% | 2%-3% |
| N | N/A | N/A | N/A | N/A |

When attempting to balance the two attributes, it can be clear by the results that at times there is a significant compromise in both of them, if the criterion is a strict consideration of equal weights. If however this criterion switches to a more flexible approach, it is possible to achieve satisfactory results for both secondary aspects of the visual environment.

In addition, the results also reflect the definition of the GlareEV index, which was used to form the visual comfort constraint; the latter takes into account both direct and total parts of the vertical illuminance, and due to its form, having the portion of the two as a variable, also accounts for the interaction of the two, in terms of direct-to-direct and direct-to-diffuse light transmission. Positions closer to the window are more prone to be affected by the increased total vertical illuminance of brighter fabrics, therefore the recommended upper limits of visible transmittance are lower when approaching the window.

Should a less strict criterion be selected, allowing a minimum of 95 % of the annual working hours to be complying with the visual comfort restrictions, the upper limits of the fabric properties become more flexible, as shown in Table 5.

Table 5 – Allowed fabric combinations for 0.75 m (VCA>0.95)

| | |
|---|---|
| S | 1 % (6 %), 2 % (7 %), 3 % (6 %), 4 % (4 %) |
| W | 1 % (6 %), 2 % (7 %), 3 % (5 %) |
| E | 1 % (8 %), 2 % (9 %), 3 % (9 %), 4 % (8 %) |
| N | No restriction |

However, glare occurrences for up to 5 % of annual working hours, associated with the VCA>0.95 limitation, get essentially translated to up to 200 hours of visually uncomfortable conditions annually. Due to the nature of visual discomfort (potentially instantaneous) and the resolution of the annual simulations (hourly time steps reflecting the available weather data), the authors believe that a strict consideration of zero glare hours, as reflected in Tables 1 to 4 is the most conservative approach towards glare-free zones in indoor environments.

## 4. Conclusion

This paper presented a methodology to recommend optical properties of shading fabrics in terms of openness factor and visible transmittance with respect to glare mitigation, energy performance, and connection to the outdoors, using the newly proposed GlareEV and VCI indices to assess visual comfort and connection to the exterior respectively. Visual comfort was used as a constraint, aiming to ensure glare free conditions for the entire portion of annual working hours, while the two contradicting objectives of lighting energy performance and connection to the outdoors were handled using four different objectives.

The results showed that openness factors should be always kept within 2 % in order to ensure visual comfort throughout the entire year, with visible transmittance upper limits ranging from 8% for southern facades to 10 % for eastern facades. For positions closer to the window, and in order to account for the potential increase of the total vertical illuminance due to the higher visible window surface, lower limits of visible transmittance are recommended. To maximize view to the outside, openness factor values close to the visible transmittance are recommended in order to minimize the direct to diffuse portion of the light transmission, while to maximize lighting energy performance, the key is increasing the aforementioned portion by using a visible transmittance much higher than the openness factor.

Future work includes the development of a unified fabric rating index that will be used in design as a fabric selection tool, as well as an investigation of the thermal implications caused by fabric selection based on the visual environment performance. Annual comfort metrics, zonal, spatial and temporal, with respect to usability and availability (Atzeri et al., 2016), should be used for such an analysis.

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