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On The Representation Of The Thermal And Visual Behavior Of A Roller Shade Material: Comparison Between Different Simulation Models

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ABSTRACT

Shading systems, if efficiently operated, can improve the internal environmental quality, namely both thermal and visual comfort, and reduce the energy consumption due to cooling needs. Roller shades represent one of the most commonly used types of shading systems, in particular in the tertiary sector. Not only they can be easily installed and maintained, but also they often represent the only design choice when existing buildings are considered. Although roller shades are characterized by a beam-beam and by a beam-diffuse transmittance, both changing according to the incidence angle, as the transmitted solar radiation decreases with the increase of it, they are typically modelled assuming equal reflectance and emissivity for both sides and perfect diffuser behavior, with transmittance and reflectance independent from the solar radiation incidence angle. Neglecting the daily variability of these properties can lead to underestimate their impact on the occupants' comfort conditions.

In this paper, different models for representing the roller shades behavior, embedded in two widely diffuse simulation codes have been compared with a set of measured data, recorded at the Bowen laboratories of the Purdue University (Indiana – USA), combining thermal (Energy Plus) and lighting simulation (Energy Plus or DIVA for Rhino). The thermal properties of the building materials and the internal gains have been calibrated for the thermal simulation, in order to evaluate better the models' capability of predicting the roller shades behavior. Then, starting from the simplest daylighting model, which assumes the roller shades as perfect diffusers, more complex characterizations have been considered and validated through the comparison with the measured data.

1. INTRODUCTION

Different studies showed that a proper operation of shading devices can reduce the energy consumption due to cooling needs and, at the same time, improve internal environmental conditions, related to both thermal and visual comfort. As underlined in Kiritmat et al. (2015), shading devices can be operated to control direct sunlight, limiting solar gains just in the cooling period. Through shading devices, it is also possible to manage the daylight distribution making it as much homogenous as possible, all over the year. At the same time, considering that thermal and visual requisites can be contrasting, the solar shading devices effects on the global building performance have to be analyzed since the early design stages, in order to define the best trade off and optimize the control strategy.

As underlined in (ANSI/ASHRAE Standard 55-2013), fenestrations with shading devices have a degree of thermal and optical complexity by far greater than that of unshaded fenestrations. Currently, different types of shading devices exist: overhangs, roller shades, venetian blinds, etc. Among them, roller shades, regardless of their internal or external installation, represent one of the shading devices most commonly used in buildings, in particular in the tertiary sector. Not only they can be easily installed and maintained, but also they often represent the only design choice when existing buildings are considered. Kiritmat et al. (2015) pointed out that roller shades constitute the

third most common type of shading devices studied in literature. Although accurate simulation approaches about their visible transmission, absorption and reflection would be highly necessary to really maximize the positive effects that they could provide, common agreement about the best way of simulating them, both from a thermal and visual point of view, still lacks.

In most of the studies roller shades are modelled as perfect diffusers (Kapsis et al. 2010; Bessoudo et al. 2010; Tzempelikos et al. 2010; Shen & Tzempelikos 2011 and 2012; Tzempelikos & Shen 2013; Yao 2013 and 2014; Ye et al. 2015), even if this can lead to inaccurate evaluations of the illuminance in certain positions (Kapsis et al. 2010; Tzempelikos & Shen 2013). Often the WindowMaterial:Shade EnergyPlus model has been used, but in some cases integrated thermal and lighting simulation codes have been expressly written. Appelfeld et al. (2012) and Hoffmann et al. (2015) simulated complex fenestration systems through Radiance to generate a bi-directional scattering distribution function (BSDF), while Chan et al. (2015) applied the Kotey's model (Kotey, Wright, & Collins, 2009), in order to correct shades' solar-optical properties and to evaluate their variation with the incidence angle.

In this paper, different models for representing the roller shades behavior, embedded in two widely diffuse simulation codes have been compared with a set of measured data, recorded at the Bowen laboratories of the Purdue University (Indiana – USA), combining thermal (Energy Plus) and lighting simulation (Energy Plus or DIVA for Rhino). The thermal properties of the building materials and the internal gains have been calibrated for the thermal simulation, in order to evaluate better the models' capability of predicting the roller shades behavior. Then the WindowMaterial:Shade and WindowMaterial:Shade:EquivalentLayer models of EnergyPlus, and the *trans* and *transdata* Radiance models embedded in DIVA, have been considered.

2. SIMULATING ROLLER SHADES MATERIAL – STATE OF THE ART

As specified in Kotey et al. (2009), roller shades consist of strands of yarn that may be woven loosely, leaving open areas, or woven tightly, with no open areas. Their specific composition operates in such a way that the incident direct solar radiation is split in two components: a portion directly transmitted through the openings, and a scattered portion that, regardless from the fact that it can be transmitted or reflected, is considered as purely diffuse. Nevertheless, the major part of the regulations or simulation codes dealing with the calculation of complex fenestration system adopting roller shades does not take into account this aspect.

The ANSI/ASHRAE Standard 55 (2013) proposes a simplified approach for calculating the solar shading system effects on thermal exchange introducing the indoor solar attenuation coefficient (IAC). It represents the fraction of heat flow, direct and diffuse, that enters the room, considering the effects of the shades. In other words, it represents the ratio of the solar heat gain coefficients (SHGC) of the glazing system, considering and not considering the shades. IAC values have been determined using the ASHWAT models (Wright J.L., 2008), and can be used in order to obtain the shaded SHGC. As concerns roller shades, the Standard assumes the IAC value is independent of incident angle of irradiation, even if it underlines that generally shades are able to both transmit and diffuse solar radiation, and, for this reason, more complex models would be needed.

As regards Europe, the reference standards are EN 13363-1:2007 (CEN, 2007) and the EN 13363-2:2005 (CEN, 2005). Both assume only the beam solar radiation coming from the sun, neglecting the sky vault's component, and a totally diffuse transmission through the shading systems (Zinzi, Agnoli, & Fasano, 2014), and can be applied to all types of solar protection devices parallel to the glazing (louvre, venetian or roller blinds), wherever installed (externally, inside glazings or internally). EN 13363-1:2007 (CEN, 2007) describes a simplified method to estimate the total solar energy transmittance of a solar protection device combined with glazing, suggested for solar energy transmittance of the glazing between 0.15 and 0.85, solar transmittance and solar reflectance of shades are within 0 and 0.5, and 0.1 and 0.8 respectively. The simplified method does not take into account either the angular dependence or the differences of spectral distribution. EN 13363-2:2005 (CEN, 2005) specifies a detailed method, based on the spectral transmission data of solar protection devices and glazings. Again, the angular dependence of transmittance or reflectance of the materials is neglected.

As concerns the simulation codes, EnergyPlus offers three different models for roller shades. The WindowMaterial:Shade model (named in the following as model A) assumes that the transmission, absorption and reflection are independent of the incidence angle. Moreover, reflectance and emissivity properties are assumed to be the same on both sides of the shades. In contrast, the WindowMaterial:Shade:EquivalentLayer model (model B, in the following) is able to consider that roller blinds can have also a beam-beam transmittance. This is assumed to be the same for both sides of the shade and equal to the openness area fraction (OF). Beam-diffuse transmittance and reflectance, and emissivity can be different for front and back side of the shade. The off-normal solar and optical property calculation of shades is based on a set of correlations developed from measurement of samples of commercially produced roller blind material with openness fraction less than 0.14 (Kotey et al., 2009). The model is

not intended for materials with unusually high values of openness and should be limited to a maximum openness fraction of 0.20. Unfortunately, at the moment Energy Plus implementation of model B does not provide daylight calculation, due to the software limitations, although the method itself has been proven to work for daylighting simulation (Chen et al. 2015). Finally, the WindowMaterial:ComplexShade can be used for modeling shades whose properties are represented by a BSDFs file, which contains the optical properties of the Complex Fenestration layers. Generally, the optical properties are provided as a two-dimensional matrix describing the basis and four two-dimensional matrices of system bidirectional optical properties. All these objects are commonly exported directly from LBNL WINDOW program.

Also Radiance provides different options for simulating roller shades, each one characterized by a different level of complexity (Chan et al., 2015). The simplest one, called *trans* (model C, in the following), is able to trace direct source rays through a semi-specular surface in order to determine the diffuse and specular transmitted components (Larson & Shakespeare, 1998). However, the *trans* model does not account for the incidence angle.

Radiance provides another model able to adjust the direct or the diffuse part of the transmitted component according to the incidence angle: the *transdata* or *transfunction* model (model D), validated for a translucent glass with diffuse characteristics (Reinhart & Andersen, 2006). According to Apian-Bennewitz (2013) the *transdata* or *transfunction* model represents the more precise model to simulate non-redirecting and forward scattering materials when BSDFs data are not available. Even if BSDFs data should be available, the geometrical radiosity method used in WINDOW does not show good agreement between simulated and measured data (Chan et al., 2015), while the *genBSDF* Radiance function, with which these data could be generated, performs well for micro-perforated shading system, but it has not been validated yet for open-weave shading fabrics.

In this paper, models_A, B, C and D have been considered and compared in order to investigate their reliability and accuracy in the evaluation of radiation and daylighting aspects in combined thermal and lighting simulation. Model A and B are considered for thermal simulation, while model A, C and D for daylighting. The Energy Plus and Radiance models based on BSDFs such as the WindowMaterial:ComplexShade have not been considered since the data needed to build the model were not available for the roller shades used in the Bowen Laboratories (Chan et al., 2015).

3. METHODS

3.1 Experimental setup

The measured data used for the models calibration and validation have been recorded throughout five days in June 2015, from the 2nd to the 8th, with a one minute measurement time-step. During this period, the roller shades have been maintained continuously closed in one of the two laboratories (named in the following as LAB1) and continuously open in the other (named in the following as LAB2). Both the heating, cooling and lighting systems have been kept switched off. Only the acquisition system, composed of a laptop and a data-logger for each room, has been maintained switched on. Regarding the external environment the global and diffuse vertical solar radiation, the global vertical illuminance, the global horizontal solar radiation and illuminance and the air temperature have been measured. The transmitted illuminance and solar radiation just after the window's pane, the air and surface temperature, the work-plane illuminance and solar radiation and the vertical illuminance have been measured in different points in the rooms (Figure 1).

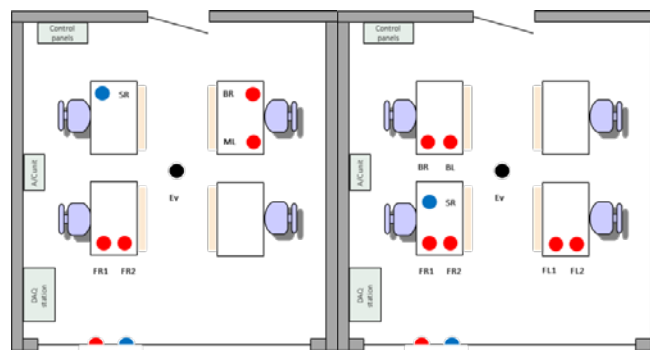


Figure 1: sensors' location in LAB1 (right) and LAB2 (left): transmitted or work-plane illuminance = red dots; vertical illuminance = black dots; transmitted or work-plane solar radiation = blue dots

3.2 Thermal model calibration and validation

Thermal simulation has been conducted through an EnergyPlus model. The external air temperature and the global horizontal solar radiation recorded during the measurements period have been used as input. A first simulation has been run for the LAB2 with open shades, starting from the nominal properties for opaque and transparent components and internal gains, as from technical documentation (ASHRAE HOF 2005) or data sheets by the manufacturers. The first day (June 2nd) has been used as a simulation warm up period, considering the internal air temperature as setpoint with and ideal HVAC. In order to improve the accuracy of the thermal model, a calibration process has been carried out by means of jEplus+EA, minimizing the differences between the internal air temperature measured and simulated in LAB2, considering the Coefficient of Variation of the Root Mean Square Error CV(RMSE) and the Normal Mean Bias Error NMBE. Only 3rd, 5th and 7th of June have been considered for calibration, while June 4th, 6th and 8th have been used for validation. Four parameters have been calibrated, as reported in Table 1, considering a variation range of approximately +/-20% across the nominal value, with the exception of the internal gains.

Table 1: Calibration input parameters

Input parameters	Material	Nominal value	Range value (*levels)	Unit measure
Specific heat	Concrete	840	672-1000	J kg ⁻¹ K ⁻¹
	Acoustic Tile	590	472-708	
	Gypsum	1090	872-300	
Infiltration airchanges		0.1	0.05-0.20	ACH
Thermal conductivity	Concrete	0.53	0.42-0.64	W m ⁻¹ K ⁻¹
	Acoustic Tile	0.06	0.048-0.072	
	Gypsum	0.16	0.13-0.19	
Internal gains (electric equipment)		36	40;50;60*	W

3.3 Roller shades modeling

The properties of the roller shades to be provided to the different models have been derived from measurements with an integrated sphere device, as specified in Chan et al. (2015), and reported in Table 2.

Model A (Table 3), as already underlined, treats the fabric material as a perfect diffuser, and it does not allow distinguishing between the internal or external shade's sides. In this case the solar and visible transmittance have been set equal to the total value, direct plus diffuse, in order to consider all the radiation passing through the material regardless from the way in which it has been transmitted.

On the contrary, model B allows separating between the direct and diffuse components of both the transmitted and reflected part of the solar radiation, even if this is not possible yet for the visible spectrum. The model is not available to consider visible radiation, so it can be used only for the thermal simulation.

The parameters for model C and model D have been calculated using two different approaches. In one case (C₁ and D₁), according to Kotey et al. (2009), the specular component of the reflected solar radiation has been considered null. However, imposing this parameter to zero it is impossible to consider the color characteristics of the shades consistently, so we tried to include (Model C₂ and D₂) in this value aspects related to locally specular reflection, which, randomly distributed because of the disposition of the yarns, accordingly to the balance equations as described in Jacobs (2014).

Moreover, model D allows changing the direct-direct component of the transmitted radiation according to the incidence angle (Reinhart & Andersen, 2006). In this work 17 off-normal values have used, obtained from the relations suggested in Kotey et al. (2009), for the specific correction factor (cf):

$$cf = \frac{\tau_{b-b}}{\tau_{b-tot}} \frac{180^\circ}{180^\circ} \quad (1)$$

where τ_{b-b} represents the direct part of the total radiation transmitted through the material and τ_{b-tot} the total amount (direct plus diffuse) for each incidence angle.

Table 2: Roller shade solar and optical properties (SS-EC02-4 dark color silver screen). Values in %

	Sol	Opt	Sol	Opt	Sol	Opt	Sol	Opt	Sol	Opt	
	Normal		15°		30°		45°		60°		Side
Beam-Total Transmission	5.0	5.0	5.1	4.9	5.1	5.0	4.3	4.1	2.9	2.7	
Beam-Beam Transmission	4.2	4.2	3.8	3.1	3.1	3.0	1.7	1.7	0.6	0.6	
Beam-Diffuse Transmission	0.8	0.8	1.3	1.0	2.0	2.0	2.6	2.4	2.3	2.1	
Beam-Total Reflectance	74.5	72.3	74.0	71.7	74.9	72.2	74.8	72.4	75.9	74.2	ext
	28.3	28.3									int

Table 3: Model A simulation values

Quantity	Value
Solar Transmittance	0.050
Solar Reflectance	0.745
Visible Transmittance	0.050
Visible Reflectance	0.723

Table 4: Model B simulation values

Quantity	Value
Shade Beam-Beam Solar Transmittance	0.042
Front Side Shade Beam-Diffuse Solar Transmittance	0.008
Back Side Shade Beam-Diffuse Solar Transmittance	0.008
Front Side Shade Beam-Diffuse Solar Reflectance	0.723
Back Side Shade Beam-Diffuse Solar Reflectance	0.283

4. RESULTS AND DISCUSSION

Three main aspects of the modelling performance have been assessed, namely temperatures as regards thermal simulation (Fig. 2), work-plane (Fig. 3) and vertical eye illuminance (Fig. 4) as for the lighting. Table 5 illustrates the models and simulation codes validated against the experimental data.

As regards thermal simulation, it is quite clear that:

1. Calibration improves the performance of the model (Fig. 2b).
2. When adding shades (Fig. 2c) the performance keeps quite good, even if the Model B seems to overestimate the temperature profile.
3. As for the entering radiation behind the glazing surface without shades (Fig. 2d), both models A and B seems to provide a good response, considering that their performance is just analyzing the glazings.

Regarding the work-plane illuminance, for space reasons, only the results obtained for the FR1 sensor located 1.5 meter from the window has been reported in the figures. The charts reported in the following underline some aspects:

Table 5: Measured quantities versus simulation output comparison

Validation aspect	Shade's model	Model	Software
Internal air temperature and transmitted solar radiation (Fig. 2)	WindowMaterial:Shade	A	Energy Plus
	WindowMaterial:Shade:EquivalentLayer	B	Energy Plus
Work-plane illuminance (Fig. 3)	WindowMaterial:Shade	A	Energy Plus
	<i>Trans</i>	C ₁ C ₂	DIVA
	<i>Transdata</i>	D ₁ D ₂	DIVA
Vertical eye illuminance (Fig. 4)	<i>Trans</i>	C ₁ C ₂	DIVA
	<i>Transdata</i>	D ₁ D ₂	DIVA

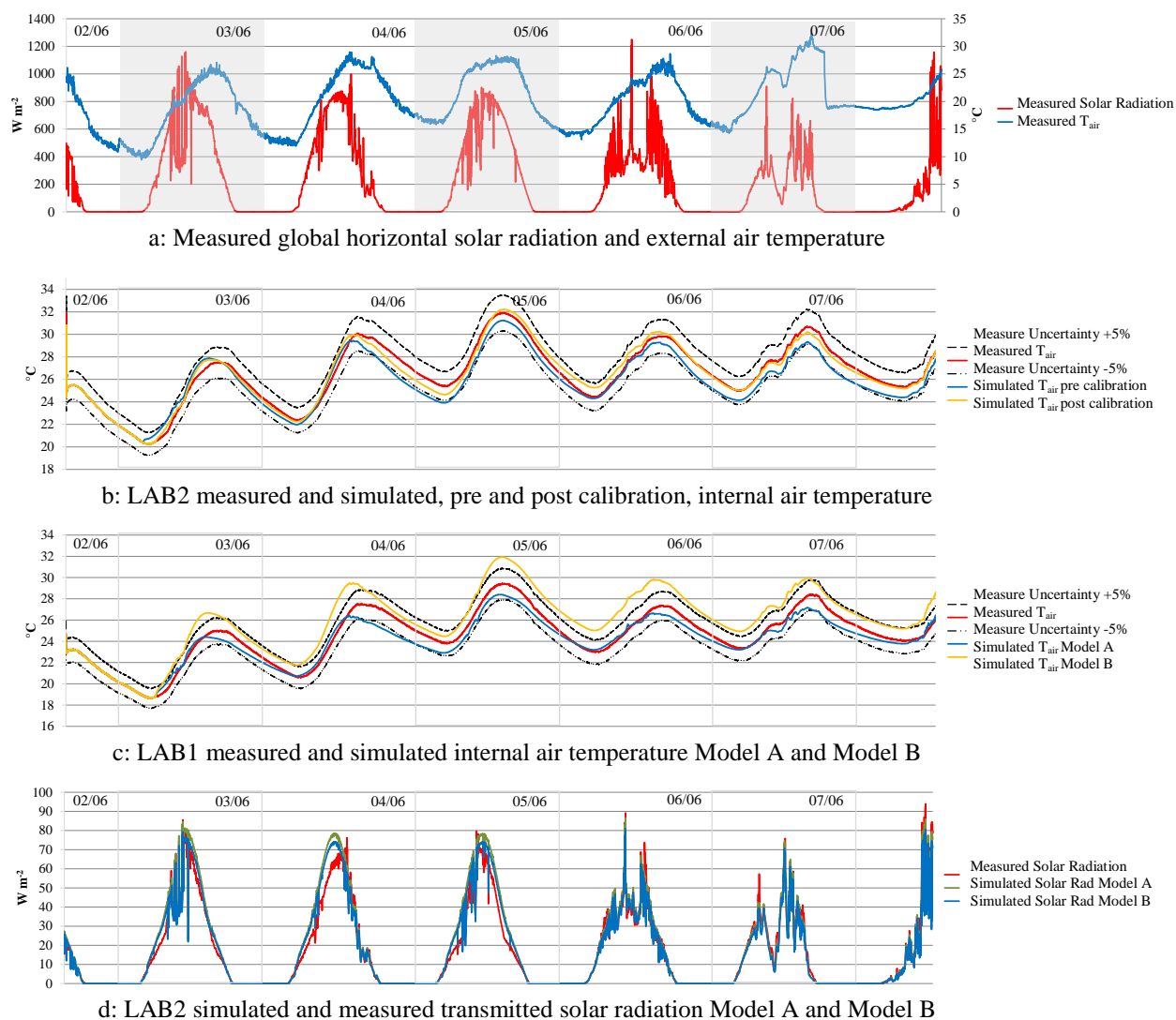
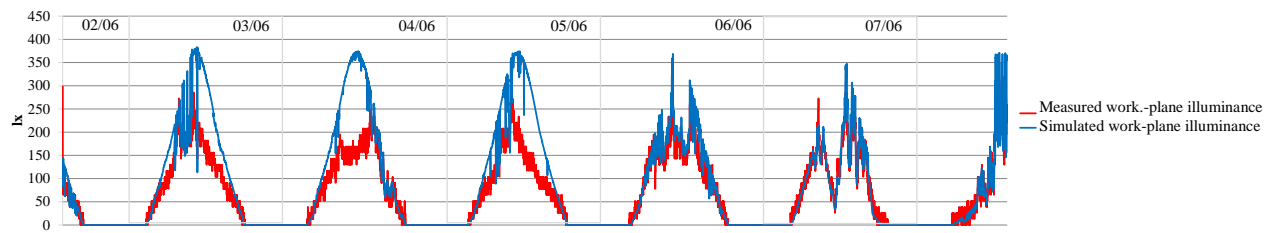
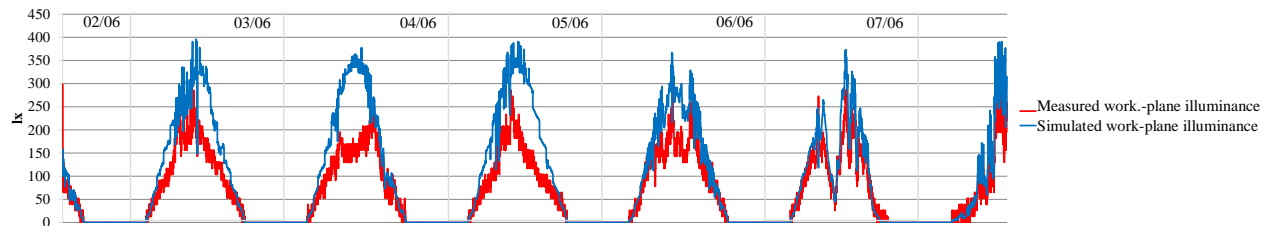
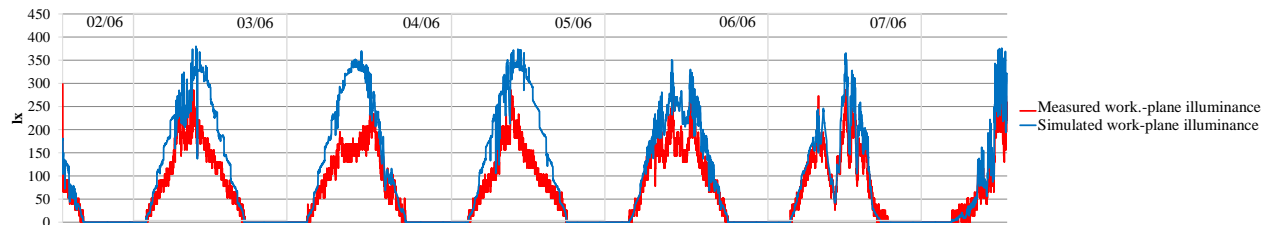
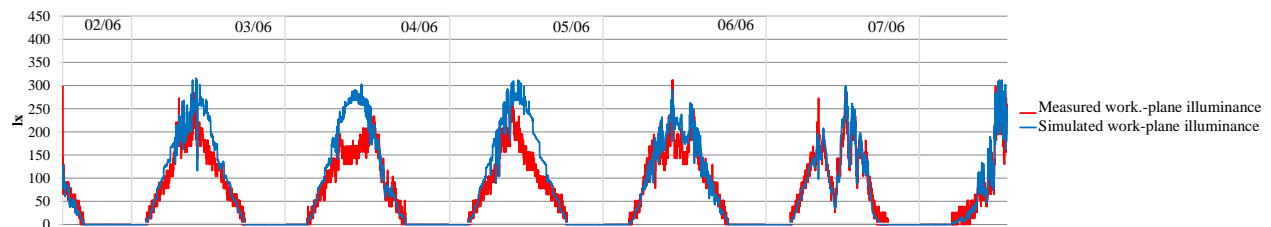
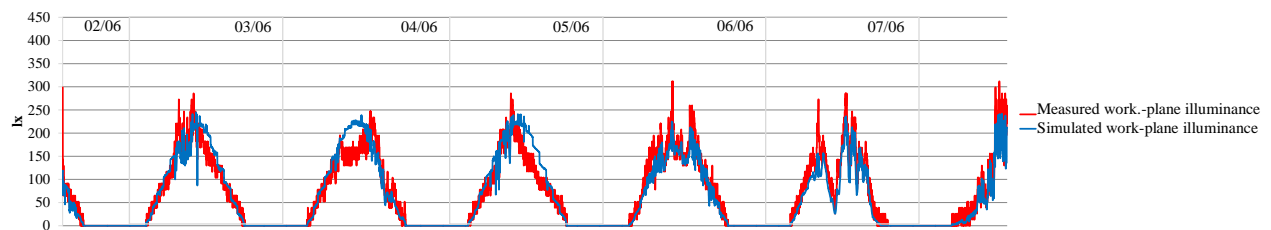


Figure 2: Thermal simulation validation

1. A poor agreement between simulated and measured work-plane illuminance values using Model A (Fig. 3a), Model C₁ (Fig. 3b) or Model D₁ (Fig. 3c) ($\rho_{b-b}=0$) when the direct-direct component prevails. In clear sky conditions, this fact can determine:
 - a. an overestimation of the available natural light
 - b. a wrong evaluation of glare occurrence
 - c. a possible underestimation of artificial light consumptions if a lighting system dimmed according to the natural light availability is considered.
2. A good agreement between simulated and measured work-plane illuminance values using Model C₂ (fig. 3d) and Model D₂ (fig. 3e) ($\rho_{b-b}\neq 0$) when the direct-direct component prevails.
3. A good agreement between simulated and measured work-plane illuminance values when the direct-diffuse component prevails.
4. A good agreement between simulated and measured vertical eye illuminance using Model D₂ (fig. 4d).
5. Also for the other positions in the room, the same trends can be underlined. As expected, increasing the distance between the sensor and the window, as happens considering the ML and the BR sensors located respectively 2.5 and 3.7 meters from the daylight source, the discrepancy between measured and simulated trend decreases. Actually, these points, especially the BR sensor, are located far enough not to be affected by the direct-direct component of the visible radiation, which is less efficiently calculated by the shade's models applied.



a: LAB1 measured and simulated work-plane illuminance for sensor FR1 – Model A

b: LAB1 measured and simulated work-plane illuminance for sensor FR1 – Model C₁c: LAB1 measured and simulated work-plane illuminance for sensor FR1 – Model D₁d: LAB1 measured and simulated work-plane illuminance for sensor FR1 – Model C₂e: LAB1 measured and simulated work-plane illuminance for sensor FR1 – Model D₂**Figure 3:** Lighting simulation validation – work-plane illuminance

Summarizing, it is possible to affirm that when a Lambertian diffuser material is used for simulating roller shades influence on visible light, the illuminance in the confined space is always overestimated when the direct-direct component prevails. At the same time, if overcast sky conditions or points enough far from the window are considered, even a simplified model which does not distinguish between the direct-direct and the direct-diffuse component of the solar radiation can provide reliable results.

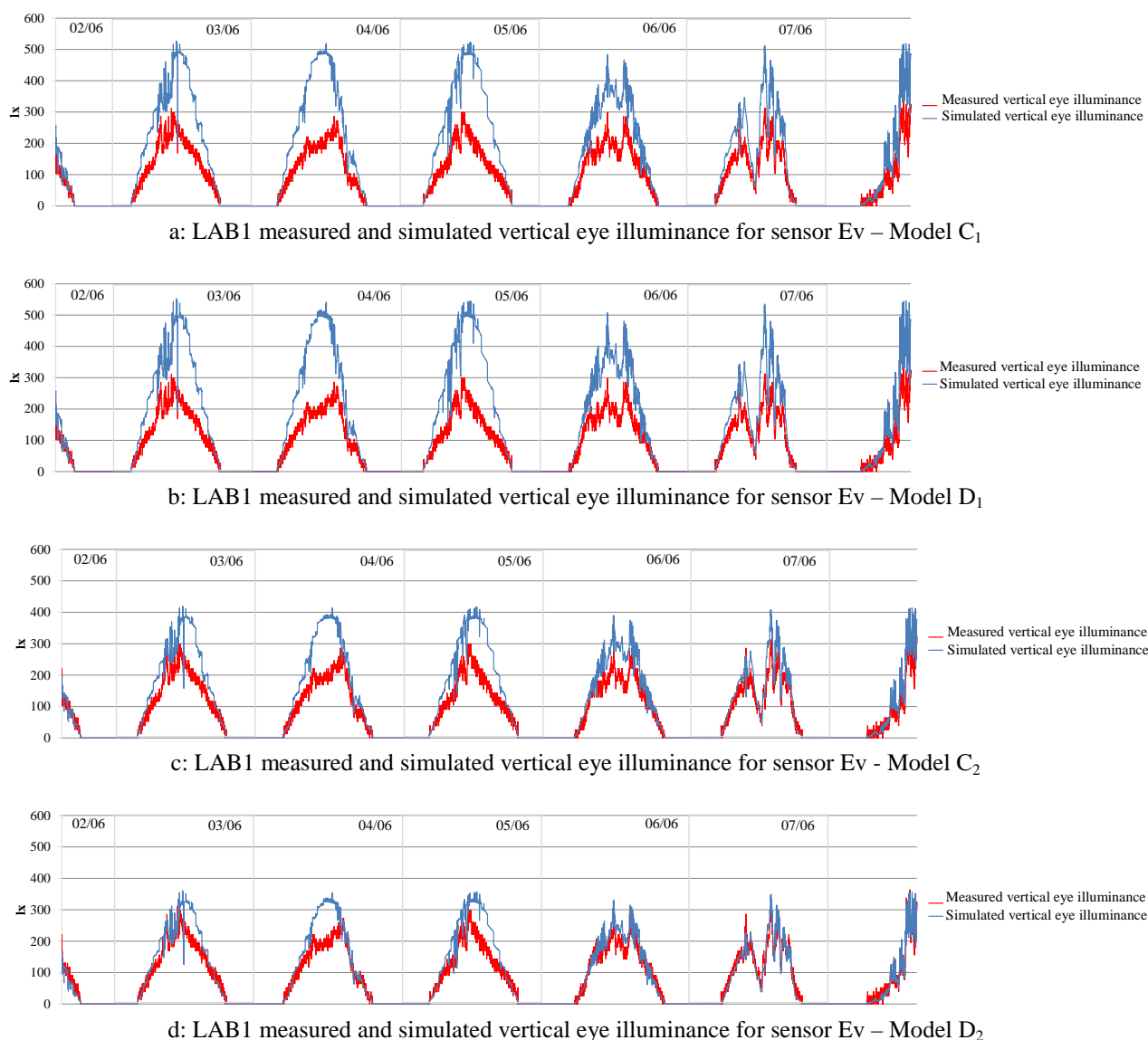


Figure 4: Lighting simulation validation – Vertical eye illuminance

6. CONCLUSION

Roller shades can have several positive effects on the building's global performance, reducing the energy consumption and improving the comfort conditions. However, in order to maximize their contribution it is necessary to consider realistically their effects since the design phase. At the moment, an agreement does not exist about which should be considered the best modelling approach.

In this paper, different models for representing the roller shades behavior, embedded in two widely diffuse simulation codes, have been compared with a set of measured data, recorded at the Bowen laboratories at Purdue University (Indiana – USA), coupling thermal (Energy Plus) and lighting simulation (Energy Plus or DIVA for Rhino). The thermal properties of the building materials and the internal gains have been calibrated for the thermal simulation, in order to evaluate better the models' capability of predicting the roller shades behavior and their contribution to the thermal balance. Then, starting from the simplest daylighting model (Model A), which assumes the roller shades as perfect diffusers, more complex characterizations have been considered and validated through the comparison with the measured data.

The results coming from the thermal simulation underlines that adding the shades' model the simulation performance keeps quite good, even if the Model B seems to overestimate the temperature profile, underestimating consequently the shades ability to control solar gains with respect to Model A. This inaccuracy could be particularly critic when the aim of the analysis consists in assessing the internal thermal comfort conditions and/or calculating the heating or cooling consumptions.

On the contrary, Chan et al. (2015) demonstrated that, thanks to the calculation approach suggested in Kotey et al. (2009) and used in the Model B just for thermal simulation, it is possible to model accurately the visual performance of a roller shading system. Further analysis is then necessary in order to understand the model overall potential.

The analysis related to the optical behavior of the roller shades, has underlined, once again, the strong correlation between the solar radiation incidence angle and the amount of visible light able to pass through the fabric material. From this point of view, the *trans* or *transdata* model (C and D) showed a good agreement between simulated and measured trends, but only considering the specular reflected component different from zero. This aspect appears even clearer considering the vertical eye illuminance trends. In this case, the Model D₂ shows the best behavior, while all the other models tend to overestimate the daylight contribution. Assuming the hypothesis that the specular reflection component is different from zero, apparently diverges from what has been established through the measurement campaign described in Kotey et al. (2009), and suggests that more measured data coming from different roller shades and from different periods of time, both in terms of duration and season of the year, are needed.

Once identified weaknesses and strengths of the different lighting models and validating them against experimental data, a further step in the work is evaluating their influence in assessing comfort and energy aspects, with the aim of understanding to which extent a more sophisticated model can improve the design decisions.

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