Angle-dependent optical properties of advanced fenestration systems—Finding a right balance between model complexity and prediction error

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Abstract

Advanced glazing systems with special spectral characteristics or light redirecting behavior are commonly applied to improve building energy efficiency and indoor comfort conditions. The angle-dependent optical properties of such advanced windows can be markedly different from those of ordinary glass. To achieve accurate building performance predictions, it is necessary to represent the physical behavior of advanced window systems at a sufficiently high level of detail in building simulation programs. However, modelers should be aware that overly complex models are also undesirable, because they are costly to develop and input parameters are difficult to obtain. There is little guidance for simulation users to select an appropriate simulation strategy with respect to atypical glazing properties. This paper introduces a new approach for analyzing the influence of angle-dependent glazing properties, taking into account the effect of location and façade orientation. The potential of this method is demonstrated using an innovative switchable glazing system based on liquid crystals. A comparison between measured and derived transmission properties based on normal angle-of-incidence is presented. Results are presented for three European cities at different latitudes and for three different façade orientations. Using this new approach, simulation users can make informed decisions about appropriate modeling strategies for considering angular optical properties in building performance predictions.

Keywords

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1 Introduction

Effective control of the solar energy gains in buildings is a basic element of high-performance building design strategies (Goia 2016; Jelle et al. 2012; Kuhn 2017). Being able to selectively reject or accept sunlight in perimeter zones can make a major contribution to achieving low-energy building operation (Lee et al. 1998; Ochoa et al. 2012; Tzempelikos and Athienitis 2007). In addition, balancing the amount of daylight with respect to visual comfort requirements such as glare and view to outside, has a positive effect on perceived indoor environmental quality and access to the health-related benefits of natural light (Aries et al. 2013; Galasiu and Veitch 2006). By following the market trend of increasing attention for more sustainable building design, it is evident that the development and application of innovative façade and window systems is a subject of growing importance

for researchers and building designers alike (Loonen et al. 2013; Quesada et al. 2012).

The properties of fenestration systems are usually characterized by component-level metrics such as g -value and luminous transmittance (τ_{vis}). These metrics are determined under standardized test conditions (e.g. ISO 9050) that measure optical window properties (i.e. transmittance and front/back reflectance) considering light under a normal angle of incidence (Asdrubali and Baldinelli 2009). Building designers and engineers use these metrics as a proxy for building performance (e.g. to assess cooling load), and subsequently compare the consequences of different glazing options as a basis for design decisions. In many countries, values for maximum g -value or τ_{vis} are prescribed for compliance with building codes (ASHRAE 2013). The same characterization metrics also play an important role in the calculation methods that determine building energy labels

(Corrado and Fabrizio 2007).

In actual operating conditions, the angle of incidence between sunlight and the building façade varies throughout the day and throughout the seasons. For most of the year, sunlight reaches the fenestration system under angles that are not close to “normal”. To cope with the differences between the standardized test conditions and actual operating conditions, various algorithms have been proposed that describe window transmission and reflection properties as a function of incidence angles between 0 and 90 degrees (Furler 1991; Karlsson 2000; Rubin et al. 1999) (Fig. 1).

These algorithms or correlations are usually based on semi-empirical formulations that combine Fresnel equations with some additional information about the window system. Validation studies have shown that this is a simple, yet very effective approach for many window types (Loutzenhiser et al. 2006). Although there have also been research efforts to include e.g. low-e and solar control coatings in these semi-empirical formulations (Roos 2001), they are mostly suited for conventional specular glazing systems. Such correlations are routinely used in building energy performance (Clarke 2001; Loonen et al. 2017) and daylighting simulation programs (Apian-Bennewitz 2013), and are sometimes referred to as incidence angle modifiers (IAM) (Clarke 2001; Duffie and Beckman 2013). These IAM correlations can either be hard-coded in the simulation software (Crawley et al. 2008), or supplied by the user in the form of input data sets that can be created through third party programs such as LBNL Window (LBNL 2017) or WIS (WinDat 2017).

Contemporary fenestration systems tend to make increased use of coatings, films or interlayers to either temper or bring more light and/or solar gains inside (Grynning et al. 2013). In addition, there is growing interest for innovative solutions such as switchable windows and other technologies with the ability to adjust optical properties (transmission, reflection, absorption) of the glazing system over time (Favoino et al. 2015; Loonen et al. 2014).

The added layers or functional materials that are used to achieve these performance enhancements may affect the

refractive properties of the window system, can introduce polarization effects, light scattering and/or non-isotropic properties. Thus, these advanced window systems can have distinct non-specular, light transmitting behavior, with complex optical properties at oblique incidence angles (Ward et al. 2011). In some cases, such as angular selective window films (Fernandes et al. 2015), the transmission properties are so different from ordinary glass that a dedicated bi-directional scattering distribution function (BSDF) is needed to accurately describe the optical characteristics of the façade system. Although various BSDF software implementations have been developed in thermal (Bueno et al. 2015; Kuhn et al. 2011) and daylight simulation programs (Goia et al. 2015; Ward et al. 2011), a main drawback with BSDF, however, is that the required input data is not widely available from manufacturers, and not easily determined experimentally or numerically. The use of BSDF data therefore tends to be limited to a small number of special situations only.

In-between the conventional glazing systems at one end, and the obvious BSDF cases at the other end, there is a large range of fenestration systems with somewhat atypical angular properties, e.g. due to coatings. The focus of attention in this study is on this category of glazing systems, for which it is unclear whether regular incidence angle modifiers in simulation models would lead to sufficiently accurate results. The following two factors play a key role in these considerations:

- Characteristics of the application. Geometrical parameters such as window tilt angle, façade azimuth and latitude of the location describe the goniometric relationship with the position of the sun and the fenestration surface(s), and determine the impact of angle-dependent glazing properties to a large extent. As a consequence, it is important to not only consider angular optical glazing properties, but also the case-specific information about location and surface orientations.
- Purpose of investigation. It may make a large difference for the appropriate level of window model resolution whether the simulation user is interested in predicting e.g. annual energy use or peak loads. Also the phase in the design process (e.g. early design phase vs. HVAC system dimensioning), plays a role in establishing the level of detail required for the investigation (Gaetani et al. 2016).

Unnecessarily complex modeling strategies should be avoided, because the window data required for such models is difficult or expensive to obtain. Complex models are usually less flexible (e.g. it is difficult to introduce different parameter variations), and it can be challenging to interpret the results, because the model structure tends to be less well-understood than is the case for simple models (Kotiadis and Robinson 2008; Zeigler et al. 2000). On the other hand,

Fig. 1 Range of angular variation for monolithic and coated materials (Reproduced with permission from Rubin et al. (1999), ©Elsevier 1999)

too simple models induce the risk of leading to significant prediction errors. There is currently very little guidance for consulting engineers and researchers to understand and decide whether they should move to a more complex modeling approach (e.g. BSDF), or whether the default Fresnel-based angular-dependence function would lead to sufficient accuracy for their case.

The objective of this paper is to introduce an approach that enables building performance simulation users to make informed decisions about a fit-for-purpose modeling strategy for considering angular optical properties in building performance predictions. Section 2 introduces the general principles of this approach and the main steps that it contains. The applicability of this approach is illustrated in Section 3, by showing the case study of a switchable glazing (SG) based on dye-doped liquid crystal (DDLC) technology. Concluding remarks are presented in Section 4.

2 Proposed methodology for analyzing the influence of angular properties

The approach proposed in this paper consists of three main parts that combine a number of research methods. The first part determines the magnitude of deviation between the optical properties of the glazing under investigation and the conventional angle-of-incidence functions employed in simulation software. In the second part, these deviations are related to case-specific factors such as façade orientation, location, and time. The third part then compiles and visualizes annual results with hourly time steps to be able to estimate the quality of representation of the optical properties at hand.

The approach consists of the following steps:

- 1) Angular optical properties
 - a) Measurements of the angle-dependent optical properties of the glazing along the two main directions, to be used as a benchmark for further comparisons. This information can also be retrieved from existing literature or data available from manufacturers of glass and glazing systems.
 - b) Computation of the 3D hemispherical view of the optical properties of the glazing and the deviation (absolute and relative) compared to a reference glazing system.
- 2) Daylighting, location, and layout
 - a) Calculation of hourly sun position and profile position for a complete year; for a specific location and orientation of the surface for which the properties of the glass are examined.
 - b) Overlapping of the optical properties of the glass and the deviations, as displayed in Fig. 2.
 - c) Computation of the relative and absolute errors among defined angular intervals and the corresponding percentage of occurrence.

- 3) Distribution and magnitude of deviations in optical properties

- a) Calculation of the distribution and magnitude of deviations, for each hour and day of an entire year, by relating time and angles of sun position with optical properties.

The next section illustrates this step-by-step procedure in more detail, by describing an application that quantifies the impact of a new type of switchable window with atypical angle-dependent properties.

3 Demonstration example: DDLC window

3.1 Introduction

This demonstration example considers the comparison between a conventional clear window type and a switchable glazing (SG) systems based on liquid crystal (LC) technology: the dye-doped liquid crystal (DDLC) window. Differently from standard glazing systems, SGs allow the variation of properties such as the luminous transmittance, solar factor, and spectrum of light upon the application of an external stimulus (Baetens et al. 2010; Khandelwal et al. 2015, 2017; Tavares et al. 2014). Current-stage DDLC windows have a layer of polymer LC materials to control the transmission of light and radiation. The layer consists of LCs typically employed in displays and a mixture of dyes specifically selected for light and radiation filtering. Switching occurs instantly, continuously and evenly across the surface of the glass. The exact working mechanism of DDLC windows has been reported elsewhere (Debijs 2010; Van Oosten 2017). Here we focus on the following higher level principles:

- At rest, alignment of LCs is homogeneous (i.e. planar) and perpendicular to the propagation direction of the incoming light. As such, the embedded dye molecules absorb most of the incident light, which results in the dark state of the system.
- In response to the application of an external voltage, the LCs have a more homeotropic alignment, which is parallel to the direction of the incident light. This arrangement causes the bright state due to the re-alignment of dye molecules and results in lower light absorption and higher luminous transmission.

This application example focuses on the luminous transmittance property of DDLC window compared to an uncoated glazing type, to estimate the differences in terms of angular dependence in relation to the contribution from incident direct light. Angular dependence of glazing systems depends on Fresnel's equations and Snell's law; however, in this research the attention is directed on the luminous transmittance ratio T . The ratio expresses the dependence

Fig. 2 Yearly sun profile coordinates are evaluated versus luminous transmittance ratio diagrams of a quarter sphere view for a vertical surface located in Eindhoven, the Netherlands. Sun profile coordinates are plotted respectively against DDLC luminous transmittance for (a) dark and (b) bright state

of luminous transmission τ_{vis} with the angle of incident light α (i.e. from 0° (perpendicular) to 90° (parallel), defined in accordance with IEA SHC Task 21 and Rosemann et al. (2005)), either in horizontal and vertical direction, and the maximal luminous transmission τ_{max} , as can be seen from Eq. (1):

$$T(\alpha) = \frac{\tau(\alpha)}{\tau_{\text{max}}} \quad (1)$$

3.2 Window characterization

To illustrate the proposed methodology, the luminous transmittances of both DDLC and a conventional glazing system were determined using a practical measurement set-up with a Perkin Elmer spectrophotometer (model Lambda 750). Higher-resolution measurements (e.g. analyzing direct and diffuse contributions separately) could possibly lead to a more accurate characterization of the DDLC properties (Jonsson and Curcija 2012; Zinzi et al. 2015), but doing so is outside the scope of the present study. In fact, one of the intended purposes of the proposed methodology is to provide an accessible approach that can be used to determine whether it is worthwhile to proceed to higher-complexity measurement methods. The measurements were taken for angles of incidence between 0° (i.e. incident light beam normal to the sample surface) to 75° (i.e. incident light beam nearly parallel to the sample surface, values above 75° were interpolated) at steps of 5° , for S (parallel) and P (perpendicular) light polarization. Both the dark and bright configuration of DDLC were analyzed. Figure 3 shows how angle variation was measured either vertically for zenith angles, and horizontally for azimuth angles. Measurements for both zenith and azimuth angles were done for DDLC in dark state; whereas only zenith angles are recorded for DDLC in bright state and for the clear glass, since the optical

Fig. 3 Schematic view of spectrophotometer measurements, from 0° to 90° . Variation of zenith (a) and azimuth (b) angle of light beam source

properties of both are isotropic (Section 3.1).

The luminous transmittance and the solar energy transmittance (transmittance of global radiation) properties of the switchable window were determined in Matlab using the calculation methods described in ISO 9050.

The following assumptions are made:

- The wavelength range was limited to the region between 380 nm and 2500 nm. τ_{vis} was calculated by integrating single wavelength results weighted with the $V(\lambda)$ coefficient for the standard illuminant D65.
- τ_{vis} results for S and P polarized light are averaged since this project aims to evaluate the effect of daylighting, which is not polarized.
- The transmission measurement considered the contribution from both diffuse and specular transmission at the same time without measuring the single component. However, this study focuses on the direct light beam which has much more dependence on the angle of incidence.
- The DDLC window is assumed to be sufficiently homogeneous to allow for meaningful comparisons with Fresnel equations that apply for clear glass.

3.3 Angular properties

Figure 4 shows the measured luminous transmittance ratios for clear glass and DDLC glass in bright and dark state. All luminous transmittance ratios are normalized with respect to the transmittance at normal angle-of-incidence, to highlight the differences in angular properties.

All functions have two common points: at 0° the function is maximum and at 90° it is zero because light incidence direction is parallel to the glass surface. The curves of DDLC glass' luminous transmittance ratios show similar trends to clear float glass; the following points can be observed:

- DDLC has different curves for zenith and azimuth in its dark state so it can be concluded that the glazing system is not isotropic. Liquid crystal layers included in the system have directionality properties altering the isotropic nature of the host glass layer. In the azimuthal direction, the luminous transmittance ratio of the DDLC dark state is less sensitive to the angle of incidence.
- Curves for zenith angles decrease rapidly in DDLC glass for both states compared to conventional clear glass in the whole angle domain, while the azimuth trend for dark state decreases slower compared to clear glass. The difference in trend can be explained by the rod-like

Fig. 4 Luminous transmittance ratios of DDLC glass and clear float glass. Measurements along zenith and azimuth of bright state DDLC and clear glass are equal due to their isotropic properties

structure of liquid crystals and their variation due to rod re-direction, as explained in Section 3.1.

Fresnel functions are symmetric and the combination of azimuth and zenith curves results in a 3D curve valid for a hemispherical view. The hemispherical view of luminous transmittance ratios is obtained through a cubic interpolation of the measurements, at steps of 1° over azimuth and zenith angles (between -90° and 90°). It should be noted that cubic interpolation can introduce significant errors for glazing systems with large differences in transmittance between zenith and azimuth angles—this type of error was considered to be negligible for the present case study. Figures 5(a), (b) and (c) show these results respectively for bright DDLC, dark DDLC and clear glass. These graphs are richer in information and provide a clearer view on how luminous transmittance of each glazing is influenced by the direction of incoming light.

The absolute and relative deviation characterizes the differences in luminous transmittance ratio curves of DDLC from clear glass subject to the same luminous conditions. Figure 6 and Figure 7 illustrate the absolute and relative deviation over the entire angular domain respectively for dark and bright state of DDLC glazing compared to clear glass.

The following conclusions for the dark state of DDLC are drawn from Fig. 6:

- The maximal absolute deviation is in the order of 8% of T_{vis} . Both positive and negative differences are observed, in line with the findings presented in Fig. 4. Positive peak values appear around 80° along zenith angles whereas negative peaks emerge at the same degrees but along azimuth angles.
- Relative deviation is lower than $\pm 10\%$ for of the angular domain ($\sim 90\%$ of the population); however, the peaks reach up to $+40\%$ when angles get closer to the vertical edges (i.e. -90° and 90°). Differently, negative peaks appear in the same region of absolute negative peaks, and it decreases while reaching 0° .

Fig. 5 Hemispherical view of luminous transmittance ratios curves, respectively for (a) dark state DDLC, (b) bright state DDLC and (c) clear glass

Fig. 6 (a) Absolute and (b) relative deviation of luminous transmittance ratios curves for dark state DDLC compared to clear glass

Fig. 7 (a) Absolute and (b) relative deviation of luminous transmittance ratios curves for bright state DDLC compared to clear glass

The following conclusions for the bright state of DDLC are drawn from Fig. 7:

- The maximal absolute deviation is positive for the whole domain and has a relatively high value of 25%. These values appear around 60° along either azimuth and zenith which is the point of maximal difference with the clear glass (i.e. close to polarization angle or Brewster's angle).
- The relative deviation is lower than 30% for most of the angular domain (~70% of the population); however, it rises rapidly when getting closer to the either horizontal and vertical edges (i.e. -90° and 90°) and it reaches peaks of 70% in the corners. These peaks are due to the differences in luminous transmittance ratio when these are very close to 0, which occurs for almost parallel incoming light beam (i.e. $\approx 90^\circ$) as can be seen from Fig. 5.

The angular transmittance curve of dark state DDLC is close to the one of clear glass in most of the angular domain, whereas bright state DDLC has a lower agreement. The dependence of DDLC on azimuth angles appears to be closer, in the dark state, to the curve of the reference glass compared to the zenithal.

3.4 Influence of daylight

In daylighting, the sun is a dynamic radiation source; therefore, the influence of sun position on DDLC luminous transmittance must be considered for an effective evaluation

of the deviations. The relation between the optical properties of the glass and the sunlight rely on the geometrical configuration of both components. Important variables are the geographical location, the orientation, the tilt, and the true local time; these elements allow the computation of the sun coordinates and enable the relation to the surfaces of the glass. Sun profile position is required to relate the luminous transmittance properties of glass to the light source, due to the fixed orientation of the surface receiving light (i.e. the normal of glass' surface) and the great distance between light source and receiver compared to the dimension of the receiver.

The evaluation of the luminous transmittance properties is done by relating yearly sun profile coordinates and a vertical glazed surface oriented toward South and located in Eindhoven, the Netherlands. The influence of different orientations and locations are analyzed in Sections 3.6 and 3.7, respectively.

A surface placed in a free field can receive light from every point within a hemisphere; however, in consideration of a vertical surface (i.e. a window) and the sun as a light source, the solution space is reduced to a quarter of a sphere due to the horizon. The sun profile coordinates are plotted against diagrams of a quarter sphere view (i.e. azimuth from -90° to 90° and zenith from 0° to 90°) of DDLC luminous transmittance ratio curves and deviations from standard clear glass. Figure 8 shows the resulting hourly analemma

Fig. 8 Yearly sun profile coordinates are evaluated versus luminous transmittance ratio diagrams of a quarter sphere view for a vertical surface located in Eindhoven, the Netherlands. Sun profile coordinates for a southern oriented glass are plotted respectively against (a)(b) DDLC luminous transmittance, (c) (d) absolute, and (e) (f) relative deviations for (left) dark and (right) bright state compared to clear glass

diagrams for South orientation of DDLC bright and dark state luminous transmittance ratio and their absolute and relative errors. Color bars have been added to represent the amount of hours in which the sun is present on each position of the one-by-one degree grid composed of solar profile angle and surface solar azimuth. Higher values mostly occur around winter and summer solstices, as indicated through the colors near the bottom and top of the hourly analemmas.

Absolute and relative errors are divided into intervals; then, the total times in which sun profile positions lie within each range are computed. Figure 9 shows the distribution of relative errors among each interval and the corresponding percentage of occurrence (i.e. relative time with respect to the total amount).

The following conclusions can be drawn:

- DDLC bright state: Deviations are between 10% and 80%, majorly concentrated between 10% and 30% (~80% of the total time). If we assume that a relative error higher than 30% is unacceptable for the purpose of the investigation, then we can conclude that in this case, the default IAM correlations will not lead to sufficiently accurate results for about 20% of the time. Based on these results, it is, however, not possible to assess at what time of the day/year the deviations occur, and how severe this impact may be.
- DDLC dark state: As previously observed in Section 3.2, the deviation of this configuration from the clear glass is relatively small, which has been confirmed by the evaluation considering sun position.

Fig. 9 Relative deviation distribution for one year of solar profile positions for South orientation. The distributions are in blue for dark state DDLC (left) and in red for bright state DDLC (right)

The identification of the times during which the highest deviations occur is necessary, to evaluate whether the influence of the resulting DDLC model is significant. Deviations can be estimated in case of daylighting simulation or results can be discarded, during times with high deviations. Consequently, these graphs must consider reasonable time interval settings of the simulation; for example, working hours.

3.5 Temporal deviation distribution

The identification of excessive deviations in luminous transmittance ratios enables the user to estimate which timeframe of a building simulation (i.e. lighting, energy) can be subject to the largest errors in the representation of the visual and thermal behavior of glazing. This allows for the subsequent assessment to determine whether these deviations are deemed acceptable. Therefore, the relative deviations are plotted against hours and day for an entire year. Figures 10(a) and (b) present both the bright and dark state DDLC for a South orientation.

In consideration of building performance simulations, it is often necessary to estimate the deviations occurring during occupied hours, for example in offices between 9:00 and 18:00.

In South-oriented façades, the relative deviations appear to be lower than 15% for dark state DDLC and 30% for bright state DDLC in most of the hours within the working timeframe. The deviation peak takes place at the beginning and end of the working day, from April to September. In light of the typical office hours (e.g. from 9:00 to 18:00) the deviations appear to have not an important influence for South-oriented façades. However, this consideration does not necessarily apply for other orientations or locations since these variables can considerably affect the distribution of deviation within the considered time-frame.

The optical properties of DDLC in dark and bright state as well as the average sun profile and azimuth angles for this orientation are computed, in order to determine the luminous transmittance or sun position ranges more prone to produce high deviations. The greatest relative deviations, for both bright and dark state DDLC, occur mainly at the presence of two conditions:

- Low luminous transmittance ratio or approaching to zero as can be seen in Fig. 11, and;
- High sun profile angles in combination with azimuth angles close to the extremity of the angular field (i.e. -90° and $+90^\circ$ compared to chosen orientation), as can be seen in Fig. 12.

The regions obtained by these conditions correspond

Fig. 10 Relative deviation distribution against each hour of a day and for each day of a year, for a vertical glazed surface oriented toward South. The plots display the distributions respectively for (a) dark, and (b) bright state DDLC

Fig. 11 Luminous transmittance ratio distribution against each hour of a day and for each day of a year, for a vertical glazed surface oriented toward South. The plots display the distributions respectively for (a) dark, and (b) bright state DDLC

Fig. 12 Luminous transmittance ratio distribution against each hour of a day and for each day of a year, for a vertical glazed surface oriented toward South. The plots displays the distributions respectively for (a) dark, and (b) bright state DDLC

to the left, the right, and the upper edges in the deviation graphs presented in Fig. 8. Moreover, the incident solar radiation for those coordinates is close to parallelism with the vertical glazed surface; therefore, its contribution can be very low due to either high reflections as well as the smaller area affected (i.e. shining in areas extremely close to the vertical surface and not getting into the space).

However, these considerations are very case-dependent since the influence of daylight varies for different orientations, locations and tilt angles of the glazed surfaces.

3.6 Impact of façade orientation

The influence of façade orientation is relevant in building performance assessments due to the seasonal variation of illumination and irradiation from the sun. The impact of different façade orientations (i.e. vertical glazed surface) is estimated for Eindhoven, the Netherlands. Figures 13 and 14 display the hourly analemma diagrams for East and West orientation of DDLC for bright and dark state luminous transmittance ratio and their absolute and relative errors.

The diagrams show the different ‘path’ of the sun and its influence on the luminous transmittance ratios and

deviations. Again the relative deviations are plotted against hours and day for an entire year, for both bright and dark state DDLC and are displayed in Figs. 15 and 16 respectively for East and West orientation.

For East and West orientations, the probability of relative error higher than 30% is reduced compared to South direction. For the case of a dark state DDLC oriented toward East, the maximal relative deviation is 10% while its overall maximum is 40% (Fig. 6). This occurs due to the lower number of hours in those regions with low luminous transmittance ratio and sun coordinates close to the edge of their domain. However, for East and West, the peaks in relative deviation take place around 12:00 for the entire year, which might require special attention since it is exactly in the middle of the working day when irradiance levels tend to be high.

3.7 Impact of location

The latitude of the considered location influences importantly the solar coordinates (i.e. height and azimuth) as well as the length of the day over an entire year. To analyze the previous findings and compare them with different latitudes, the

Fig. 13 Yearly sun profile coordinates versus luminous transmittance ratio diagrams of a quarter sphere view for a vertical surface oriented East and located in Eindhoven, the Netherlands. Sun profile coordinates are plotted respectively against (a)(b) DDLC luminous transmittance, (c) (d) absolute, and (e) (f) relative deviations for (left) dark and (right) bright state compared to clear glass

relative deviation distributions have been computed for two additional locations: one at higher latitude; Stockholm, Sweden, and; one at lower latitude; Rome, Italy. The distributions of relative deviations for a vertical glazed surface oriented toward South are shown in Figs. 17 and 18 respectively for Stockholm and Rome. Before analyzing the results, it is important to note that some of the differences and shifts in the hours or in the length of the day are due to the difference in longitude between Eindhoven, Stockholm and Rome; since all are part of the UTC (i.e. GMT +1) time zone.

The diagrams confirm that the conditions of low luminous transmittance ratio and solar angles close to the edge of the angular field are common for each location. The major

differences are due to the different distribution of the solar profile angles, since at lower latitudes the sun reaches higher angles at noon compared to those at higher latitude. During the day, the sun gets to higher angles and for longer periods; therefore, reaching those regions of the deviation diagrams having greater differences, as can be seen from Fig. 19. The impact of this parameter can be most appreciated for DDLC in bright state; the amount of area colored by cyan (i.e. approximately a deviation of 30%) is greater with decreasing latitude from Stockholm (Fig. 17(b)) to Eindhoven (Fig. 10(b)) and then Rome (Fig. 18(b)). It can therefore be concluded that the results of building performance predictions of DDLC switchable windows for higher latitudes would be less affected by wrong representation of the optical properties.

Fig. 14 Yearly sun profile coordinates versus luminous transmittance ratio diagrams of a quarter sphere view for a vertical surface oriented West and located in Eindhoven, the Netherlands. Sun profile coordinates are plotted respectively against (a)(b) DDLC luminous transmittance, (c) (d) absolute, and (e) (f) relative deviations for (left) dark and (right) bright state compared to clear glass

Fig. 15 Relative deviation distribution against each hour of a day and for each day of a year, for a vertical glazed surface oriented toward East. The plots display the distributions respectively for (a) dark, and (b) bright state DDLC

Fig. 16 Relative deviation distribution against each hour of a day and for each day of a year, for a vertical glazed surface oriented toward West. The plots display the distributions respectively for (a) dark, and (b) bright state DDLc

Fig. 17 Relative deviation distribution against each hour of a day and for each day of a year, for a vertical glazed surface oriented toward South and located in Stockholm. The plots display the distributions respectively for (a) dark, and (b) bright state DDLc

Fig. 18 Relative deviation distribution against each hour of a day and for each day of a year, for a vertical glazed surface oriented toward South and located in Rome. The plots display the distributions respectively for (a) dark, and (b) bright state DDLc

Fig. 19 Yearly sun profile coordinates versus luminous transmittance ratio diagrams of a quarter sphere view for a vertical surface oriented South. Sun profile coordinates are plotted against DDLc luminous transmittance relative deviations for dark state respectively for: (a) Stockholm, Sweden; and (b) Rome, Italy

4 Concluding remarks

The angle-dependent optical properties of many advanced glazing systems, e.g. with coatings or interlayers, are markedly different from the angular behavior of simple, specular glazing systems. Significant attention should therefore be paid to the accurate representation of such effects in dynamic building energy simulations and climate-based daylight predictions. Too simple models can misrepresent the actual optical properties under oblique angles, which may lead to unreliable predictions or unfavorable decisions in the design stage. Too complex models, on the other hand, are inflexible and may require input data that is either expensive or very difficult to obtain. Identification of a fit-for-purpose modeling complexity level for angle-dependent optical properties is therefore of primary importance for the development of sensible simulation studies. In this paper, the focus is on providing guidance in cases that are in the grey area between ordinary specular glazing systems and advanced fenestration systems with complex light scattering/redirecting behavior for which the use of BSDFs is the obvious way to go.

The goal of this paper was to introduce a framework that can help simulation users in comprehending and deciding about the necessary level of modeling resolution for including angle-dependent optical window properties. The approach starts by determining the deviation between (i) actual optical properties determined through a set of simple measurements or data obtained from the international glazing database (IGDB), and (ii) angular properties derived through Fresnel equations. In a next step, these deviations are linked to the path of the sun through the sky, and the correspondingly occurring angular variation relative to the fenestration surface. In this way, it is possible to derive a frequency distribution that shows the extent of deviation between the actual optical properties, and those derived from the Fresnel equations. When this information is visualized as a function of time of the day and year, it becomes a powerful tool to analyze the resulting prediction error over time. In turn, this can be used to evaluate whether the observed range is deemed acceptable, or if there is a need to move to a higher modeling complexity, which may require obtaining much more extensive measurement data.

The usability of the new approach for analyzing the impact of angle-dependent glazing properties was illustrated by showing the case study of an innovative switchable glazing type, based on dye-doped liquid crystals. The results showed the possibility to take non-isotropic optical properties into account, and also highlighted the importance of graphically representing dynamic sun profile angles. Moreover, it was found that façade orientation (East-West vs. South) plays a large role in determining the impact of deviations between

actual and assumed angular glazing properties. For locations with lower latitude, the potential risk for errors was found to be higher, because the angle between the position of the sun and the (vertical) façade plane is more often in the region where significant deviations occur.

The decision about whether to move to a higher-resolution fenestration model depends on many contextual factors. Most notably, the model abstraction errors should be related to the purpose of the investigation and the magnitude of other uncertainties that have an impact on the predictions. For example, a window modeling approach might be accurate enough to support the ranking between two design options, but the same approach may lead to significant errors when trying to predict the actual energy use of a building. It is therefore difficult to provide generic error ranges beyond which a simpler modeling approach would no longer be valid. To cope with such issues, Gaetani et al. (2016) have presented a systematic procedure for deciding about the right level of modeling complexity for occupant behavior models—another main source of uncertainty in the domain of building performance simulation. In future work, it would be interesting to explore if a similar approach can be used in conjunction with the method presented in this paper.

An associated step for future work would be to implement the proposed visualizations in the graphical user interface of widely-used building performance simulation programs. It is expected that these visualization enable modelers to make informed decisions about the required window modeling complexity level, and it would therefore be valuable if such information can be seamlessly integrated in the simulation workflow.

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