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Daylight Simulation Workflows Incorporating Measured Bidirectional Scattering Distribution Functions

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Abstract

Daylight predictions of architectural spaces depend on good estimates of light transfer through skylights, windows and other fenestration systems. For clear glazing and painted surfaces, parametric transmission and reflection models have proven adequate, but there are many cases where light-scattering, semi-specular shading and daylighting materials defy simple characterization. Something as commonplace as fabric roller shades and venetian blinds may turn daylight prediction into guesswork, and numerous advanced systems on the market tuned specifically to enhance daylight are not sufficiently characterized to distinguish their performance. In this paper, we describe new tools available to handle novel and specialized fabrics, materials, and devices using *data-driven* modelling of bi-directional scattering distribution functions (BSDFs). These representations are usually tabulated at constant or adjustable angular resolution for efficient point-in-time and annual daylight simulations. We describe a variety of BSDF simulation workflows, including some of the tools and methods that make advanced analysis possible, and highlight some of the current challenges. We conclude with a discussion of future work and how such data might be created and shared worldwide.

Keywords: bidirectional scattering distribution function; daylighting; complex fenestration systems; windows

1. Introduction

In the Intergovernmental Panel on Climate Change (IPCC) 2021 Climate Report [1], climate scientists unequivocally linked human-caused emissions to extreme weather. The report estimated that the world will likely reach or exceed 1.5°C increased global temperatures within the next two decades and without immediate action, temperatures are projected to increase to 2.4°C by 2050 and 4.4°C by 2100. Evidence of this increased temperature is in the news with alarming frequency. In 2021 alone, there have been deadly floods in Germany, Belgium and China that have killed hundreds with more than 1000 people still missing [2]. Extreme heat waves with temperatures over 49.6°C hit the upper Western United States which has normally cool climates, killing an estimated 1260 people

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[3], while Europe experienced its hottest summer on record, according to the European Union's Copernicus Climate Change Service. With a 1.5°C temperature rise, 30-60 million people worldwide are projected to live in areas where the average heat in the hottest month is too high for humans to function well [4]. The IPCC indicates that rapid, transformational change will be needed to limit global warming to 1.5°C by the end of the century.

Energy efficiency is one of fifteen stabilization wedges proposed by Pacala and Socolow for reducing carbon emissions [5]. Lighting accounts for 15% of global electricity consumption while in the U.S., windows in residential and commercial buildings are responsible for 4.33×10^{18} J (4.2×10^{15} Btus) or 3668 kWh per capita of primary energy use [6]. Daylight and solar radiation through windows can be a carbon-free resource to offset electric lighting requirements in buildings insofar as it does not increase the energy demand for cooling [7]. Dynamic windows and operable window attachments, for example, help regulate the diurnal and seasonal effects of solar radiation and daylight in buildings with an estimated technical potential to save $1.0-2.8 \times 10^{18}$ J ($0.98-2.62 \times 10^{15}$ Btus) in total energy use (lighting, heating, and cooling) annually in the U.S. compared to the current building stock [8].

The buildings industry has responded to the call for action by ratcheting down energy budgets in energy efficiency standards, introducing innovative technologies to the market, developing product rating and labeling systems (e.g., European Solar-Shading Organization (ES-SO [9]) and Attachment Energy Rating Council (AERC [10]) for window attachments), and providing rebate and incentive programs for consumers. To meet more aggressive demand-side management goals, industry has also developed solutions that account for the interactive effects between building systems (i.e., envelope, lighting, and HVAC) at increasingly higher levels of spatial and temporal granularity [11]. In parallel with these trends is the public's increasing awareness and demands for higher indoor environmental quality. View and non-visual aspects of daylight have been linked to health and wellness in buildings [12], [13], [14], [15] and new codes and voluntary standards have been introduced to recognize design solutions that meet wellness criteria, e.g., EN 17037. Activities within the International Energy Agency (IEA) Solar Heating and Cooling (SHC) Programme Task 61 [16] have identified daylight as an important strategy for reducing the significant increase in lighting energy use associated with circadian entrainment if satisfied solely with electric lighting.

In support of these activities, considerable R&D has been invested over the past decade to improve the accuracy and speed of Radiance[1] [17] simulation tools that model solar radiation and daylight in buildings. Calculations based on radiosity algorithms have been largely replaced with the far more accurate ray-tracing algorithms. Order of magnitude increases in computational speed have been achieved with ray-tracing-based matrix algebraic approaches [18], [19], [20], [21], [22], [23]. Models that characterize the angle dependent transmittance and reflectance properties of optically complex, coplanar and non-coplanar fenestration systems, i.e., bi-directional scattering distribution functions (BSDFs), have been validated against gold standard ray-tracing methods and monitored data from full-scale outdoor testbeds [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35]. These new tools enable "climate based" daylight modeling (CBDM) where timestep calculations are conducted using input weather data. Compare this to the use of static daylight factors based on a standard CIE overcast sky which was prevalent a few decades ago. Or consider how climate-based thermal energy simulation tools have been available to industry since the early 1990s [36], [37]: ray-tracing based algorithms were previously too computationally expensive, slow, and impractical for use in annual analysis but are now within reach of any practitioner. Spectrally-resolved models for quantifying the non-visual effects of solar radiation have been developed more recently and are currently available for point-in-time analysis [38].

The objective of this article is to inform stakeholders of the current state of Radiance daylight and solar radiation modeling tools and demonstrate their application on the wide variety of modeling challenges facing industry with

[1] Radiance is an open-source ray-tracing toolset developed initially by G.J. Ward at the Lawrence Berkeley National Laboratory in 1987 and has continued to develop via Ward, LBNL, and the worldwide open-source community.

the goal of increasing awareness and use in today's workflows. The article focuses on the algorithms that constitute the core engine behind daylighting software tools. Discussion of software tools that link this computational engine to user-friendly graphical user interfaces is outside of our scope. As such, this article provides the audience with intermediate to expert knowledge[2] in the science of daylighting with an overview of the state-of-the-art and a review of needs going forward to achieve routine and broad use of the advanced tools. Section 2 provides background information on the technical concepts surrounding use of the ray-tracing methods. Section 3 provides example workflows to demonstrate application of these new methods to potential users. Section 4 reviews future needs to support stakeholder requirements for codes and standards, rating and labeling programs, and rebate and incentive programs.

2. BSDF Data Representation versus Application

We first discuss the distinctions between parametric and data-driven BSDF data (Section 2.1) then describe how sampling the BSDF via Monte Carlo ray-tracing affects the speed and accuracy of the result (Section 2.2). BSDFs describe the spatial distribution of light scattered by a fenestration material or system's transmission and reflection as a function of incident radiation (Figure 1). An accurate BSDF enables one to calculate insolation and appearance precisely for any window system, rather than approximating it as some combination of pure specular and Lambertian components. Advanced mathematical (i.e., "parametric") models exist for Bidirectional Reflection Distribution Functions (BRDF) [43], [44], and even simple transmission models may be sufficient for glazings [44], but advanced fenestration systems have by design particular transmission characteristics that require some form of measurement. The best practice for such systems is to measure all important incident and scattered directions using a goniophotometer[3] and convert these to a tabulated[4] *data-driven*[5] BSDF representation. Such a BSDF may then be used as input to climate-based daylight and other annual simulations using matrix-based methods as described by Klems in [18], [45] and Section 2.3. Higher resolution representations (see e.g. [46] for definitions and resolution schemes) may be needed for point-in-time rendering and glare analysis.

2.1. Parametric and data-driven BSDF models

Parametric BSDF models are commonly used in computer graphics. As examples, a clear glazing or an ideal mirror can be described by a Dirac delta function for the direct transmitted or mirrored direction, respectively, and zero elsewhere. Examples for scattering models include the Phong model [47], Cook-Torrance model [48], Ashikmin-Shirley model [49], and Ward-Geisler-Moroder-Dür model [50]. These parametric models are widely used for generic material descriptions in simulations, but their assumptions must be reviewed if applied to façade systems that differ from those initially considered. If the system matches the initial assumptions, using these models can be an efficient approach. For example, if the scattering properties of a window attachment can adequately be described as a combination of a Lambertian (diffuse) component and a possibly anisotropic[6] scattered specular (direct) component, fitting measured data to derive parameters for the Gaussian model in [50] is effective, and well-suited for Monte Carlo sampling[7].

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[2] For introductory material on the subject, see [39], [40], [41], [42].

[3] An instrument that measures the spatial scattering of light off a surface or device.

[4] "Tabulated" BSDF models are described by a discrete set of values for a finite set of directions (i.e., tabulated values of the function).

[5] In our context, data-driven implies that a BSDF was derived from interpolated measurements.

[6] Anisotropic materials exhibit varying scattering behavior, where the sample fenestration material can be symmetric over a single axis (venetian blind), over two axes (woven fabric), or unsymmetric (random microgeometry). Isotropic materials exhibit the same scattering behavior irrespective of how the sample material is rotated (e.g., glass).

[7] Monte Carlo methods draw samples from a specified probability distribution to integrate a similar function.

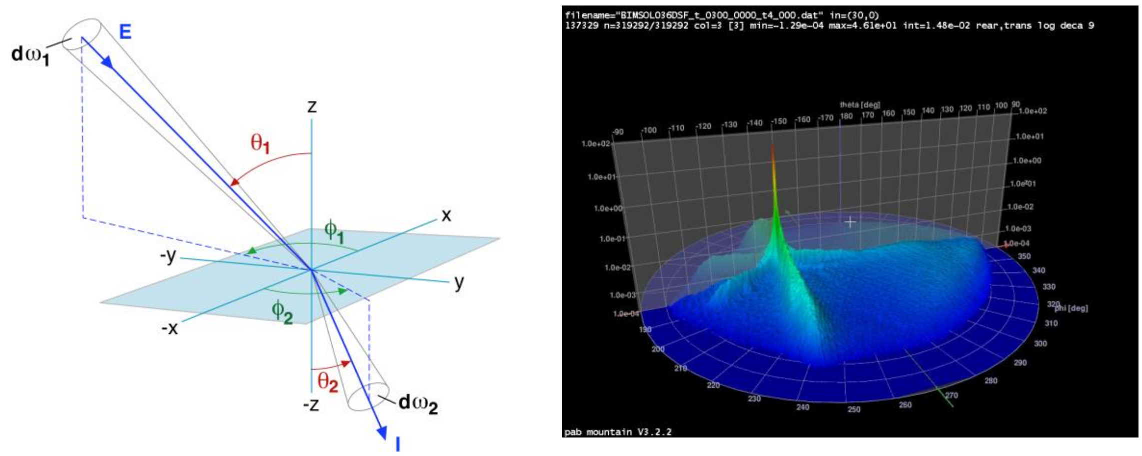


Figure 1. Left: Incoming and outgoing angles of transmission relative to the sample fenestration material (shown as a blue plane). Source: LBNL. Right: Distribution of light transmitted through a woven fabric shade. This Directional Scattering Function (DSF) = BTDF * cos(θ_s) distribution is given for incident direction $\theta_i = 150°$, $\phi_i = 90°$, where BTDF is the Bidirectional Transmission Distribution Function and θ_s is the outgoing scattering θ angle. The transmission distribution is generated from goniophotometer data. Source: HSLU.

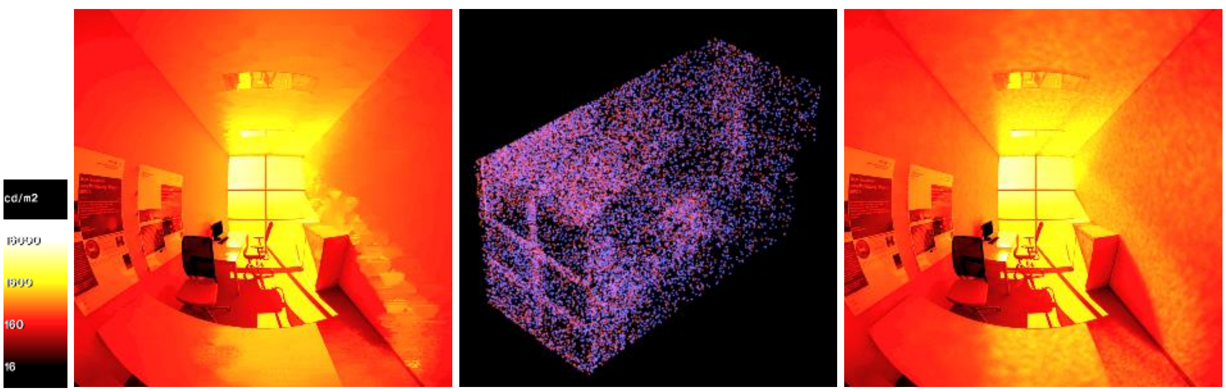
Another approach is to derive parametric models for specific classes of daylighting systems. For example, Kotey [51] and Jonsson et al. [52] derived models for roller shade fabrics based on angle-tube measurements of total and diffuse transmittance using a spectrophotometer. Instead of goniophotometer [53] measurements for numerous incident angles, these models allow us to define a BSDF for solar heat gain evaluations from a single measurement at normal incidence. Using an isotropic scattering assumption, Wienold et al. [54] measured normal-normal transmittance, normal-diffuse transmittance, normal-hemispherical reflectance, and the cut-off angle to create a simplified model for daylight and glare analysis of roller shade fabrics.

However, advanced daylighting systems are often designed to have special light scattering and redirecting properties. These generally cannot be represented via generic parametric models. Here it is best to take a universal approach that allows angularly resolved measurement data to be provided as a data-driven, tabulated BSDF data set to the daylighting simulation engine [35], [55]. In this sense, parametric models can also act as an intermediate step and be used to represent a daylighting system in a virtual goniophotometer set-up to generate tabulated BSDF data (e.g., [27], [28]). This avoids having to reprogram the simulation tool to handle new models, which is far from trivial in a Monte Carlo ray-tracer. In this approach, the magnitude of the associated error depends mainly on the chosen resolution of the tabulated BSDF (i.e., step-wise data) and how well it approximates the parametric model (i.e., continuous analytical model).

2.2. General application of BSDFs and efficient sampling

BSDFs can be used in daylighting simulations in two ways: directly in the ray-tracing process as a material description, or in matrix-based annual simulations. In both applications, low resolution BSDF data (e.g., resolved following the 145x145 Klems or Tregenza basis) provide fast, approximate results. Indeed, sampling higher-resolution BSDFs (e.g., 4096x4096 tabulated data) presents a challenge for the Monte Carlo calculation in a backward ray-tracing approach – but this is exactly what we need to accurately represent the direct solar component for calculations of discomfort glare and other metrics requiring granular spatial modeling of sunlight [56], [57], [58], [32], [33], [59]. Sunlight, whether transmitted, scattered, or reflected, needs to be predicted at highest accuracy due to its high intensity, especially for systems that allow specular transmission or reflection, e.g., for fabrics with openness, blinds, or (mirror) louvers. If available, proxy geometry (e.g., geometry of the slats of a venetian blind) can be used for the direct component simulation [60]. Unfortunately, this is not always possible, either because the geometry is not available (e.g., for fabrics) or prohibited by the manufacturer because of intellectual property protections. Resolving peaks in a high-resolution BSDF data set especially tests the computational limits of a backwards Monte Carlo ray-tracing algorithm.

The backwards ray-tracing problem can be potentially mitigated by using a forward-tracing algorithm, such as photon-mapping (Figure 2). In backward ray-tracing, light propagation is solved starting at the receiver and potentially misses narrow light sources behind a randomly sampled BSDF. In contrast, the forward emission of "photons" ensures that all sources are accounted for[8]. Photon-maps are *view-independent* and can be reused to render multiple images, animations or the illuminance at different sensor points. To reduce calculation bias and visible noise [61], photons are typically not rendered directly, but use a limited light-backward ray-tracing pass. Pre-computation of the photon density accelerates this step [62]. The light-forward generation of photon maps is similar to but generally more efficient than filling the irradiance cache[9] in the case of caustics, e.g., in the presence of directional light sources and directional scattering, which is a typical use case for high-resolution BSDF models. Other than the irradiance cache, photon maps are by default computed even for regions of the scene model that contribute little or not at all to the final result, leading to either huge photon-maps or to noise due to low photon density. The user should restrict the storage of photons from distant sources to those contributing to the result by the definition of photon ports[10]. In the case of large scene models, regions of interest should be defined, to store photons only in the evaluated zones.



Backward ray-tracing (52,800 s) | Photon distribution (view-independent) (696 s) | Rendering based on photon-map (1824 s)

Figure 2. Example processing time and typical sampling artefacts with a data-driven model (Laser Cut Panel (LCP) in the upper window zone) by backward ray-tracing with irradiance cache (left) and photon-mapping (center and right) [59]. The former has problems to resolve caustics (e. g. the LCP's deflection to the ceiling) and produces artefacts where the BSDF is not sufficiently sampled (e.g., along the wall). Photon-mapping relies on the rapid forward distribution of photons and avoids problems of backward ray-tracing but produces typical noise artifacts where the photon density is low (e.g., on the desk in the foreground). Source: HSLU.

[8] Photon-mapping tracks packets of luminous flux, which we casually call "photons" for simplicity.

[9] Irradiance caching is a common method for sharing indirect illumination across surfaces to save calculation time.

[10] Apertures where photons enter the space, e.g., windows and skylights.

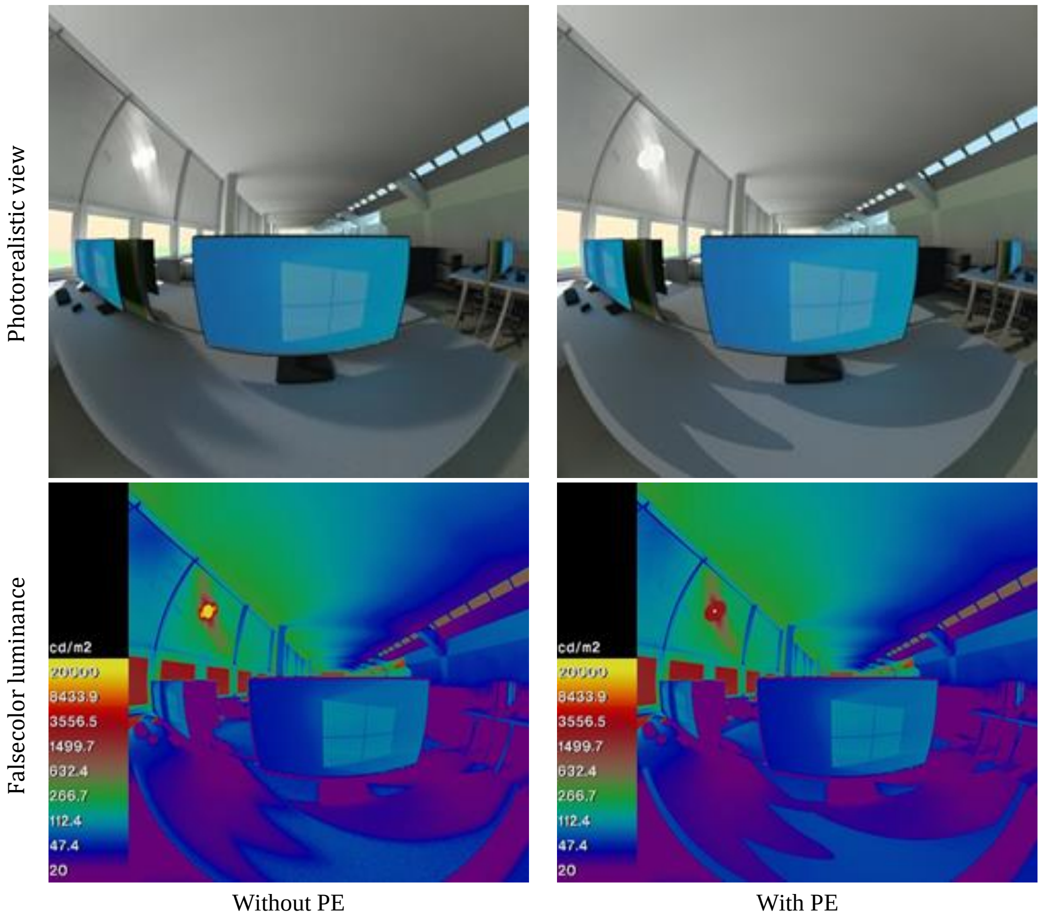


Figure 3. Simulation without (left) and with (right) peak extraction (PE) from the high resolution BSDF data (max. 4096x4096). Note the differences in the sharpness of the shadow patterns and the size and luminance of the sun patch. The maximum luminance is 163,000 cd/m^2 (left) and 4,260,000 cd/m^2 (right). Source: Bartenbach.

Even so, both backward ray-tracing and the photon-mapping method spread out the direct component from the sun over the respective resolution of the BSDF. To overcome this limitation, a “peak extraction” (PE) method [63] has been developed that allows one to simulate the direct solar contribution at its real size and spread, while efficiently using the underlying BSDF data set for the scattered light. The algorithm analyzes tabulated BSDF data for every ray that hits the respective daylighting or shading system surface, and determines whether the underlying distribution has a peak in the tested direction (e.g., peak in the distribution shown in Figure 1 right). By checking surrounding directions, the algorithm determines if there is a strong local peak in the distribution. If so, the peak is replaced with a direct specular component where the transmission is calculated from the local BSDF value. In Radiance, the peak extraction method has been implemented in the *aBSDF* material [64]. By assigning this material, the user tells the software to look for a possible peak in direct transmission. This results in well-defined shadow contours as well as a sharp view through the fenestration system modeled by *aBSDF* (Figure 3), the view being of particular importance in contrast-based glare evaluations.

The approaches described have different strengths and weaknesses. The use of proxy geometry yields correct shadow patterns and realistic appearance but is incompatible with the matrix calculation approach, or might be impossible due to the unavailability of geometry data. The photon-mapping approach allows us to simulate deflected peaks to any direction in the BSDF distribution but has the disadvantage that the sharpness and intensity of any directional contribution, whether directly transmitted or specularly reflected, is determined (and thus limited) by the resolution of the underlying BSDF data. The PE algorithm in turn improves the simulation of the specularly (direct) transmitted component through a system represented through its BSDF data but does not cover off-specular or reflected peaks. Choosing the best method involves multiple considerations.

2.3. Matrix-based methods

Matrix algebraic methods rely heavily on tabulated BSDF representations to characterize complex fenestration systems (CFS) efficiently and accurately. BSDFs in the forms of matrices can represent in-plane (e.g., Venetian blinds) and out-of-plane (e.g., awning) shading systems and can be used in three-, four-, five-, and six-phase methods to model the flux transfer through these systems. The matrix-based methods started with the two-phase, or daylight coefficient method, where the source to point-of-interest flux transfer is stored as a matrix [19]. Specifically, with the two-phase method, the relationship between the discretized sky luminance and indoor illuminance points is stored as a matrix, which is then used to compute any indoor illuminance by multiplying it with a vector of the real sky luminance value. (Note: The first "phases" of the matrix-based methods are computing matrices, and the last "phase" is matrix multiplication.) The equation for the two-phase method is:

$$I=D_cS \quad (1)$$

where D_c is the daylight coefficient matrix storing flux transfer from the discretized sky patches to indoor points and S is the matrix of sky patch luminous intensities over the desired period. Even though the two-phase approach drastically decreases the time required to simulate multiple time steps, changing any part of the model requires recomputing the matrix. If a designer were to investigate the performance of five different window systems, five matrices would need to be computed, even though the rest of the model remains the same, resulting in wasted computation. This situation becomes acute for operable shading systems. The two-phase method was later extended by breaking down the flux transfer into two and three parts to address this challenge, hence the three- and four-phase methods. With the three-phase method, the flux transfer from the sky to indoor points was divided into two parts: 1) sky to the outer window surface, and 2) inner window surface to indoor points, resulting in two matrices: daylight and view matrix. The CFS is usually characterized as a BSDF in a square matrix format. The equation for the three-phase method is thus:

$$I=VTDS \quad (2)$$

where V is the matrix storing flux transfer from window to indoor points, T is the matrix characterizing the CFS transmission, D is the daylight matrix, mapping flux transfer from the sky to outer window surfaces, and S is the sky matrix. With the four-phase method, the flux transfer from the sky to the outer window surface is further broken down into two parts: 1) sky to facade apertures, and 2) facade apertures to window outer surface, resulting in a new facade matrix and a modified daylight matrix. Facade apertures are virtual planes that encapsulate a non-coplanar system, such as an external shade or operable awning. Thus, the flux transfer from facade aperture to window surface captures the directional transmittance of the non-coplanar system. The equation for the four-phase method is:

$$I=VTFDS \quad (3)$$

where F is the facade matrix and D is the modifier daylight matrix. The three- and four-phase methods allow the designers and engineers to perform parametric analysis on different parts of the model. However, by representing shading systems as square matrices, we are trading directional resolution for convenience. Since the window is usually represented as a 145x145 matrix, small high-intensity light sources, such as the sun, are underestimated for applications such as visual comfort. Variable resolution BSDF, such as tensor tree BSDF, was developed to adapt to the system's incident and outgoing resolution while retaining simulation efficiency [58]. The five-phase method developed by McNeil [65] separates the diffuse and direct components:

$$I=VTDS - V_d T D_d S_d + C_{ds} S_{sun} \tag{4}$$

where the V_d, D_d, and S_d are the direct-only part of the view, daylight, and sky matrices. C_{ds} is the direct sun coefficient matrix and S_{sun} is the sky matrix containing only the sun. The six-phase method combines the four- and five-phase methods in a similar manner, removing the direct sun component from the four-phase part of the equation and adding it back using a tensor tree BSDF.

The capability of photon-mapping to efficiently calculate the contribution by directional sunlight allows one to partially avoid the complexity of the five-phase method employing contribution photon-maps [66]:

$$I=VTDS_s + C_s S_{sun} \tag{5}$$

with S_s being the diffuse-only sky matrix at low (e.g., Tregenza) resolution, C_s the sun coefficients (in analogy to the five-phase method but including internal inter-reflections) and S_{sun} the sun-only sky matrix.

There are other simulation methods that employ similar principles to accelerate annual simulation, including discretization of the sky and separation of the diffuse and directional flux transfer. Daysim discretizes the sky into 145 patches and performs direct solar calculation on 58 location dependent and representative solar positions [21]. Four-component methods divide the flux transfer into direct and indirect components due to sky and sun respectively [67]. Subramaniam also proposed a variant of the two-phase method that separated the direct-sun component, similar to the five-phase method [68]. Combining the efficient modelling of directional sunlight by photon-mapping with the three-phase method to account for diffuse sky-light allowed CBDM with real sun geometries and motivated the development of a photon-mapping solution for daylight coefficients [69], [70].

Some of these methods are illustrated with examples in the following section.

3. Example Simulation Workflows

3.1. Matrix-based methods

Matrix-based methods involve generating then multiplying the matrices for each time step of an evaluated period (e.g., year). Generating the various matrices using the Radiance backward ray-tracer consists of three parts: 1) ray sender, 2) ray receiver, and 3) the scene objects that sit in-between the sender and receiver. Rays are sent to the scene, interacting with objects before arriving at the receiver, where the rays are binned by exiting direction and stored as a matrix. Shared sender and receiver specifications allow matrices to be subsequently combined at a common flux interface. The Radiance *rfluxmtx* program can be used to facilitate matrix generation:

rfluxmtx sender receiver scene

For example, computing annual workplane illuminance resulting from a set of Venetian blinds in a side-lit office in San Francisco can be achieved using the three-phase method:

Step 1: Generate the matrices

Computing the view matrix (V) involves the sender, the grid, and the receiver, the window. The grid consists of the virtual sensor point location and direction. The *rfluxmtx* command is thus:

rfluxmtx -I – window.rad scene.oct < grid.pts > view.mtx

Similarly, computing the daylight matrix (D) involves the sender, the window, and the receiver, the sky. The *rfluxmtx* command becomes:

rfluxmtx window.rad sky.rad scene.oct > daylight.mtx

Generation of sky matrix (S) requires weather data, usually direct normal and diffuse horizontal irradiance. Weather data for major cities and airports are available as Typical Meteorological Year (TMY) weather data, and one of the formats is the EnergyPlus weather (EPW) file. For example, a San Francisco weather file can be converted to a sky matrix file using the commands:

epw2wea SFO.epw sfo.wea; gendaymtx sfo.wea > sfo.mtx

Before computing results, the Venetian blind system (matrix T) needs to be in the form of a tabulated BSDF. One cannot easily measure the directional transmittance and reflectance of a macroscopically structured shading system, such as Venetian blinds. Generating a BSDF of such a system relies on measurements of a flat sample of the slat which are input with the geometry of the system into a virtual goniophotometer such as the Radiance *genBSDF* program. In this case, *genBSDF* generates a venetian.xml file containing the BTDF and BRDF of the system in a square matrix format compatible with the view and daylight matrix dimensions.

Step 2: Multiply the matrices

Having all the necessary matrices, one can then multiply the matrices to obtain illuminance at each virtual sensor for each time step in the weather file:

dctimestep view.mtx venetian.xml daylight.mtx sfo.mtx > grid_results.txt

Workplane illuminance data from one of the sensors can be visualized using a temporal false color map (Figure 4).

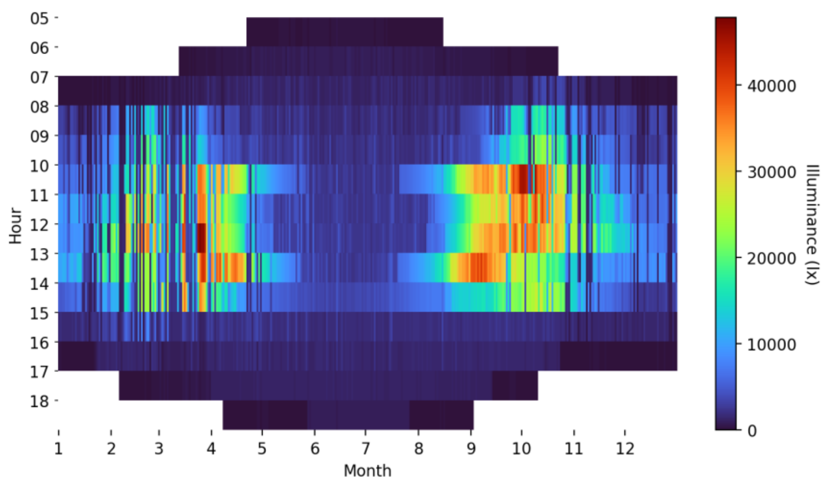


Figure 4. Workplane illuminance (lx) data for each hour (y-axis) and day (x-axis) of the year. Hourly data were generated from the three-phase simulation. Source: LBNL.

Software libraries can support automatic set-up of matrix/phased methods, e.g., the Python-based Framework for Radiance Simulation Control (*frads*) [71]. These libraries automate the complicated workflow, thus lower the entry barrier for beginners and reduce human error.

3.2. Solar heat gain analysis

Apart from providing visual contact with the outside, daylighting and glare protection, fenestration systems are responsible for solar heat gain management. Solar heat gains are typically beneficial in heating seasons and unwanted in cooling seasons. The ability of a fenestration system to manage solar heat gains is represented by its Directional Solar Heat Gain Coefficient (DSHGC) or angle-dependent g-value [72], which is a measure of the total fraction of incident solar irradiance that is transmitted into the building through a fenestration system for different incoming directions. The DSHGC of geometrically complex fenestration systems can be determined in the laboratory by applying a calorimetric measurement method ([73], ISO 19467:2017 [74], ISO 19467-2:2021 [75]). Such measurements are important for verification of DSHGC that are calculated analytically or through BSDF-based workflows.

The DSHGC has two components: 1) the optically transmitted solar irradiance, and 2) the fraction of solar radiation which is absorbed in the system and then released by convection and radiation to the indoor environment. The solar irradiance that is optically transmitted through a scattering fenestration system can be effectively represented by a broadband BSDF covering the solar spectral range. The spatial resolution of BSDF datasets for building energy analysis can be kept low, e.g., the Klems BSDF format is used in EnergyPlus. Calculation of transmitted solar irradiance based on a BSDF representation of fenestration systems allows the calculation of the shortwave radiative energy that is absorbed by each indoor surface. In cases where indoor surfaces have very different thermal mass (e.g., lightweight furniture versus massive walls and floors), the distribution of shortwave solar radiation in a room can have a noticeable impact on the calculation of indoor air temperatures and energy demands.

BSDF datasets for the solar spectral range are difficult to determine experimentally. Further investigation is still required to determine whether broadband signals (e.g., with InGaAs detectors) are suitable for experimentally deriving a BSDF in the near infrared (NIR) spectral range. For many shading devices, however, the assumption of approximately spectrally constant behavior can be made (consistent optical behavior across the visible and near infrared range), e.g., in the case of white or metallic slats for venetian blinds. In those cases, BSDF datasets determined with silicon diode detectors (visible spectrum) can be used for building energy analysis as well. It must be noted that the reflection component of the BSDF dataset of a shading device is also important in determining the solar-control function of the device and thus must be paid the same attention as the transmission component.

In order to obtain the BSDF for the solar spectral range of a fenestration system as required by building energy simulation programs such as EnergyPlus, the BSDF dataset of the shading device must be combined with the BSDF of a glazing unit. Tools such as LBNL’s WINDOW software [76] offer the Klems method [18] for this purpose. LBNL’s WINDOW software can be applied to generate a Klems BSDF of a glazing unit and a shading device for the solar spectral range from the individual spectrally resolved and broadband BSDF datasets of the glazing unit and the shading device, respectively. Spectrally resolved BSDF datasets of non-scattering and isotropic components such as glass panes are determined analytically by LBNL’s WINDOW from the normal-hemispherical transmittance and reflectance, and from coating information of the glass pane. The calculation of the BSDF of a fenestration system from the BSDF of its individual component layers generates the angle-resolved absorptance of each component as a by-product. This information is then used by the building energy simulation tool to solve an energy balance at each surface of the multilayer fenestration system (ISO15099 [77]), which determines its temperature distribution and the second term of the DSHGC. In doing so, the gas properties of the gaps between the glazing and shading layers are explicitly taken into account.

The following steps illustrate how to generate a Klems BSDF for the solar spectral range of a fenestration system and how to apply it to building energy calculations using EnergyPlus. Here, it is assumed that the fenestration system is composed of a glazing unit and a shading device.

1. Obtain a Klems BSDF of the shading device for the visible spectral range, assuming that the spectral behavior of the shading device is flat. A BSDF of shading fabrics or Lambertian venetian blinds can be generated for the entire solar spectrum using geometrical models within WINDOW and spectral data in the Complex Glazing Database (CGDB) library. In cases where neither the assumption of constant spectral properties nor of the mentioned geometrical models is valid, a BSDF for the solar spectral range must be experimentally determined with a goniophotometer and an InGaAs detector as well as silicone-based detectors.
2. Import the Klems BSDF file of the shading device in the LBNL WINDOW shading layer library.
3. Define a layer-by-layer glazing unit from the International Glazing Database (IGDB) in the LBNL WINDOW software. Define an additional layer with a shading device associated with the uploaded BSDF data.
4. Calculate the BSDF of the whole fenestration system. In this step, the WINDOW program applies a spectrally-resolved version of the Klems method to combine the BSDF of individual layers in a multi-layer fenestration system.
5. The resulting BSDF can be exported in the input text format of EnergyPlus (idf) to be directly applied in building energy simulations. The file includes the angle-dependent absorptance values for each layer of the fenestration system, which are required for EnergyPlus calculations. The relevant EnergyPlus objects to simulate the irradiance transmission through windows by means of BSDF are “WindowMaterial:ComplexShade” and “Construction:ComplexFenestrationState”.

3.3. Annual energy and illumination performance simulations

Climate-based daylight modeling is used typically to determine whether a design meets prescribed annual performance targets for energy efficiency, demand-side management, comfort and health, and indoor environmental quality. For early stages of design, where changes occur on a day-to-day basis, annual simulations are often used to support big-picture decisions (e.g., massing, building orientation, window-to-wall ratio, external shading). As the design matures, detailed annual simulations such as five-phase methods can be used to explore options in more detail and assess trade-offs in performance (e.g., vary the type of window to assess the effect on daylight autonomy).

For development of regulatory standards, design guidance, or to support programmatic decisions made by corporations, utilities, and other institutions, the workflow can involve large sets of parameterized simulations to assess sensitivity and evaluate cost-benefit tradeoffs, e.g., assessing the impact of new regulations that reduce prescribed window-to-wall area ratios or technical potential of a class of fenestration technologies to support net zero energy goals (workflow example 3.3.a, [78], [79]). Similarly, development of new technologies can involve tens of thousands of simulations coupled with optimization algorithms to identify solutions that best meet multi-objective criteria (workflow example 3.3.b, [80], [81]). In the former case, speed concerns can be addressed with computational resources such as cluster computers to identify gross trends. In the latter case, where critical performance issues must be identified prior to costly investment in scale-up toward a manufactured technology, e.g., daylight-redirecting technology, absolute accuracy matters, so parameters for generation of the BSDF and its representation and sampling levels during time-step simulations must be set carefully and is often studied in combination with laboratory measurements of prototypes to confirm observed trends.

Workflow example 3.3.a: Assess the energy savings potential of exterior shading

In this example, daylight simulations are coupled with a building energy simulation engine to evaluate the total energy savings potential of exterior outdoor shades. Data from this type of study can be used by utilities to assess measures for their demand-side management technology portfolio, for development of energy-efficiency design guidelines for architects, or to benchmark the performance of emerging technologies being developed by manufacturers. Twelve types of outdoor coplanar shades are modeled with five window-to-wall ratios, two daylight control modes, and four window orientations, totaling 480 permutations per climate zone.

The three-phase method is well-suited for this type of parametric study, where the matrix T is interchanged to represent each of the twelve outdoor shades with or without an indoor shade deployed for glare. Because EnergyPlus does not allow state reinitialization within each timestep and its internal daylight and glare calculations use radiosity- or approximate ray-tracing based methods, the workflow involves: 1) pre-computing hourly schedules for daylight and discomfort glare using Radiance (or other integrated tools that rely on Radiance such as OpenStudio [82], Ladybug/Honeybee [83], [84], and Fener [85]), then 2) using the schedules to compute annual lighting and HVAC energy use. The three-phase method is used to compute hourly daylight illuminance across a grid of points. Solar irradiance incident on a grid of points across indoor room surfaces are also computed with the three-phase method using material properties in the solar spectrum instead of just the visible range. Absorbed solar energy of the fenestration system is modeled using the absorption BSDF for each glazing and shading layer as described in Section 3.2. Hourly glare ratings (Daylight glare index (DGI) and Daylight glare probability (DGP)) are computed using the Radiance *evalglare* program [86], [87] and used for indoor shade control. The resultant 480 sets of schedules are fed into the *EnergyPlus* energy simulation program to compute annual heating, cooling, and lighting energy use. An example analysis using this method is given in [78].

Workflow example 3.3.b: Assess the building-to-grid demand response potential of dynamic windows

In this example, switchable, dynamic windows are evaluated to assess their load modifying potential to support utility grid stabilization goals as intermittent renewable energy sources become more prevalent. Such studies can help utilities evaluate how integrated building control systems can support the evolving grid and can be informative for manufacturers of dynamic window and shading products. A three-zone electrochromic (EC) window is controlled to minimize HVAC and lighting energy cost according to a time-of-use rate schedule where demand charges are considerable during critical peak periods. Thermal loads from window and lighting loads are forecast over a 24-h prediction horizon to determine how best to control the HVAC thermostat setting. Daylight, view, and comfort serve as constraints. Spawn-of-EnergyPlus [88], which uses fully dynamic state-based simulations within each timestep, is used for the overall simulation. The three-phase method is used to model the EC window and the baseline operable shade condition. Daylight matrices are computed for each window zone while view matrices are computed for each sensor in the workplane sensor grid and for each room surface. Each of the three zones of the EC window can be tinted to four states and for each of the four states, the BSDFs for visible transmittance, solar transmittance and solar absorptance for each glazing layer are derived from the IGDB. The overall workflow involves the following steps:

Step 1. Compute the set of matrices that captures the flux transport in the visible and solar spectrum range using the *rfluxmtx* program

a) Surface incident solar radiation view matrices:
   for each EC window zone and for each room surface:
   rfluxmtx floor zone1 scene_sol > floor_zone1
b) Daylight matrices:
   for each EC window zone:
   rfluxmtx zone1 sky scene > zone1_sky

Step 2. Multiply the matrices at each timestep using the Radiance *rmtxop* program to obtain workplane illuminance data to determine spatial daylight autonomy (sDA) and lighting energy use, absorbed solar radiation at each glazing layer (Qabs), surface incident solar radiation (Qsol), and vertical illuminance at the eye (to approximate glare). Using the weather forecast horizon over the next 24 h, derive the sky matrices (sky_vis and sky_sol). The following data are then computed:

1) Daylight workplane illuminance:
   for each EC window zone and each EC tint state
   rmtxop workplane_zone1 state1_vis zone1_sky sky_vis > sDA_state1_zone1
2) Incident solar radiation for each room surface using the solar sky matrix (sky_sol):
   rmtxop floor_zone1 state1_sol zone1_sky sky_sol > Qsol_state1_zone1
3) Absorbed solar radiation for each fenestration layer:
   rmtxop state1_abs zone1_sky sky_sol > Qabs_state1_zone1

Step 3. At each timestep, daylight illuminance, discomfort glare, room surface solar irradiance and layer-by-layer absorbed solar radiation for each window zone and tint state for the next 24 h are fed into an optimization algorithm to determine the tint states of the three window zones, HVAC thermostat setting, and lighting dimming level that minimize energy cost over the forecasted 24 h. An example analysis using this method is given in [81].

3.4. Point-in-time rendering

While many types of lighting analysis consider different daylight hours throughout the seasons (i.e., annual simulation), individual point-in-time renderings are still an indispensable tool for evaluating the visual appearance of a space. For example, Figure 3 shows the view from a particular vantage point for one workstation at a single time of day and year yet gives a very good idea of what one might experience in this space. The image also provides a reference point for discomfort and disability glare analysis. In another case, we may wish to see what a measured BRDF looks like under specific lighting. Or, we may have performed an entire annual simulation, but wish to pull out and examine a few typical or exceptional times we identified.

Figure 5 is a point-in-time rendering that illustrates many of the features of the BSDF representation and rendering methods we have described. The scene contains isotropic and anisotropic data-driven BSDFs interpolated from measurements as well as BSDFs derived from geometric models. The bronze head, flowerpot and silver goblet materials were all converted from isotropic measurements [89]. Our derived BRDF Extensible Markup Language (XML) files were one-tenth the size of the original binary data on average and demonstrate that we can ingest measured data from a variety of sources. The aluminum mural and velvet tablecloth were interpolated from anisotropic data [89] and extended to all incident and scattered directions. The sheer curtain was simulated using *genBSDF* from a virtual sample of loose-weave fabric model, which was re-applied to the folded geometry shown. The complex fenestration consisting of the window, frame, and vertical blinds was modeled as a unit using proxy geometry as described in Section 2.2. This reduces noise in the indirect illumination calculation without affecting the view or shadow patterns.

Section 2.3 described how matrix-based methods are employed in annual simulations to compute irradiance values. Matrix-based rendering techniques further allow us to visualize a fixed view or set of views over a selected time interval, equivalent to the daylight coefficient or three-phase method. Rather than a simple matrix that relates illuminance locations to sky or window coefficients, we generate contribution images for each sky or window component and multiply these against the appropriate vector, summing the results to get an approximate result. This saves us much computation, especially if we wish to animate an entire year. The payoff comes when generating the final renderings, which take only a few seconds per frame to produce the image, where most of the time is spent in hard disk i/o.

Figure 5. A point-in-time rendering using many BSDF features and materials in Radiance. Source: G.J. Ward.

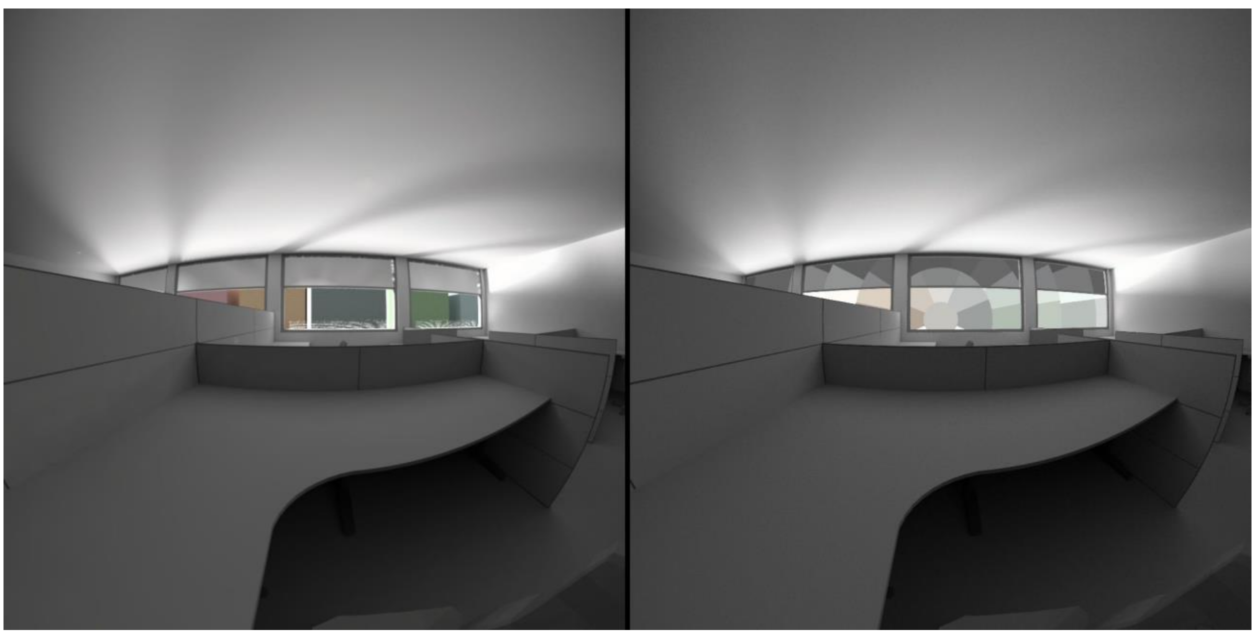


Figure 6. Direct rendering (left) versus matrix-based rendering (right) for a split window system with a daylight-redirecting louver in the upper area and a venetian blind system in the lower area. Source: G.J. Ward.

Parametric BSDF functions provide more photorealistic renderings, whereas data-driven BSDF representations in tabulated form can create perceptible differences in the rendered image [58]. Increasing tabulated BSDF resolution yields more photorealistic renderings, where the angular patches become smaller and less pronounced, and artifacts around direct specular highlights or blurred indirect specular reflections are reduced [26]. A comparison between a direct point-in-time rendering with blind proxy geometry to a matrix-based result using a Klems BSDF subdivision of the window is shown in Figure 6. The upper portion of the window uses a daylight-redirecting louver system and the lower portion uses a venetian blind. Clearly, the window detail for the straight rendering is superior, but the indirect daylight is modeled well (i.e., within 6% for this image) using the matrix method at a tiny fraction of the cost.

The importance of photorealism and spatial accuracy for point-in-time or annual performance evaluations differs depending on the analysis objective. For daylight autonomy or solar heat gain analysis, where the metrics are largely insensitive to small changes in position of the sensor or area of the incident surface, the Klems representation (145 directions per hemisphere) is sufficient. For analysis of discomfort glare (see Figure 3) or the effects of direct sunlight (i.e., annual sun exposure), high resolution BSDFs that better match the actual angular distribution and intensity of transmitted and reflected flux of the fenestration system are needed for accurate performance assessments [90], [91].

4. Future Work

4.1. State-of-the-art and new BSDF libraries

Although prior efforts to establish a BSDF library have occurred [92], [93], at present there are no maintained, comprehensive libraries of shading and daylighting products for daylighting analyses and rating of fenestration systems. LBNL developed an open-access library and rating methods within the purview of the AERC, but the database is still under development and is focused on providing low-resolution (i.e., Klems) BSDF data primarily for solar heat gain analysis of residential shade products. In 2019, LBNL and Fraunhofer ISE initiated a project to define a cloud-based, building information modeling (BIM)-compatible, internationally recognized BSDF database portal that would facilitate querying and access to child databases hosted by research institutions, manufacturers, and other sources worldwide [94]. Certification of data would be left to the discretion of providers of child databases. The project concludes in Spring 2022 and is anticipated to create a framework for distributing BSDF data (tabular data plus associated metadata tags) to end users for a small fee.

Under the IEA SHC Task 61 Subtask C activity, participants have been collaborating to define library submission requirements unique to daylight-specific BSDFs with activities that include model definition and optical measurement procedures, inter-laboratory comparisons, and definition of schema for querying the library [46]. Methods for generating BSDF data for daylighting applications are relatively new and are anticipated to evolve as measurement procedures, simulation tools, and daylight metrics improve. As such, IEA SHC participants have identified several key issues:

1) Adequate metadata (i.e., documentation) will be critical for maintaining a transparent database that can be updated and improved incrementally. Documentation will need to include methods used to measure the material or fenestration system (e.g., instrument, bench set-up, parameter settings, definition of sample orientation), proxy geometry with necessary qualifiers (e.g., assumptions of simplified geometry, expected differences from manufactured product), tools used to process the raw measured data to its final BSDF tabular form (e.g., software version, interpolant settings), references to empirical validation of methods, and other salient information needed to evaluate the sufficiency and accuracy of the library entry. If the method is based on a standard, then details on which sub-method and assumptions within the standard will need to be provided since there are often multiple pathways for compliance (e.g., EN 14500, EN 17037). For each entry, the metadata should enable an end user to replicate generation of the final tabular datasets from the raw input data.

2) The range of simulation activities conducted by industry spans a broad range of purposes: a BSDF library could include non-certified entries generated for unique architectural projects and certified entries for manufactured

products generated using approved, standardized methods. The former may be adequate for decision-making at the conceptual design level, where historically the daylighting community has generated their own solutions [27], [95]. As building certification programs and standards start to incorporate comfort and health into their metrics, the latter may be needed prior to final specification and approvals. Given evolving methods and tools, placeholder data could be provided as characterization methods are developed, validated, and standardized. Labeling and certification procedures indicating intended use of the data would be needed to differentiate between the various types of entries. Procedures for ensuring compliance with standards in the data submission process and renewal of certifications would need to be worked out amongst shading and daylighting manufacturer organizations (e.g., AERC, ES-SO) on a global scale. Certified data entries would have a cryptographic label indicating approval by the certification organization.

3) For some systems, particularly those with specular transmission or reflection, "high resolution" data (e.g., tensor tree) could be generated erroneously from library entries that have inadequate underlying models and/or raw data, leading to unintended errors. To qualify library entries, metrics are under development[11] that would provide an effective, achievable resolution value based on the raw data and simulation settings used to generate the data-driven BSDF. Alternatively, preemptive tools could be used to prevent generation of tabular BSDFs if the underlying data are of insufficient angular resolution.

4) To find materials or single layer shade system data in the library that meet specified criteria, BSDF-specific metrics will need to be defined so that innovative daylighting products can be located by consumers when the database is queried (e.g., direct-direct visible transmittance of less than 0.01 for specular transmission). These metrics will need to be defined carefully to avoid unintentional exclusion of products from consideration on a proposed project.

4.2. Need for fast and reliable simulation approaches for annual daylight glare evaluations

More and more standards and certification systems are including daylighting in their criteria, where glare caused by daylight is an essential part. The European Standard EN 17017, for example, requires that the DGP not exceed a maximum value (0.35, 0.40, or 0.45, depending on the level of recommendation) for more than 5 % of the usage time of the space. This in turn implies that the architect or lighting designer has the appropriate simulation software available to perform these annual calculations. Since a building is always developed over numerous variants to the final design, software is needed that can perform such evaluations quickly and reliably. Wasilewski et al. [96] summarize in their review of existing spatio-temporal methods for daylight glare assessment that current methods (i.e., vertical illuminance-based calculations such as DGPs and eDGPs) rely on approximations that simplify the calculation of daylight glare. These more efficient and faster calculation methods come at the expense of accuracy and lead to results that are inconsistent with user acceptance feedback. They conclude that further research and development is needed to enable fast but at the same time highly accurate simulation methods for daylight glare evaluations. Recent developments based on an "imageless DGP", a multi-phase method using vertical illuminance and a set of potential glare sources [97] or based on adaptive spatial and temporal sampling [98] are moving in this direction, but easy-to-use solutions are not yet on the designers' desks. For these new developments, tabular BSDFs will still be needed.

This demand is further emphasized in the context of daylighting systems, which are usually characterized in simulations using BSDFs. For daylight glare metrics including contrast terms, such as DGP or DGI, the underlying BSDF data resolution and thus minimum glare source size significantly affect the results. However, it is not yet

[11] Metrics and calculation methods are being developed by Greg Ward and Lars Grobe.

known whether these metrics are sufficient in contrast glare situations with very small light sources, such as the sun, or if minimum solid angles should be applied. Results from an interlaboratory round robin test conducted as part of the IEA SHC Task 61 [99] indicate that there are large differences in simulated outcomes depending on simulation method (e.g., with or without PE) and method of generating the BSDF dataset and that, for example, evaluations according to the EN 17037 are thus not reliably possible without clearer definitions of methods. In addition, current research on the DGP metric under contrast glare conditions (i.e., presence of small but bright glare sources like the sun with low vertical illuminance at the eye) is currently ongoing and should result in revisions to the formula soon [100].

Summarizing, this means that research and development is needed not only for the simulation methods (including the correct integration of BSDFs), but also for the daylight glare metrics themselves.

5. Conclusions

Daylight simulation has made significant progress over the past two decades, with increased adoption of climate-based simulation and new means to characterize complex fenestration systems. Data-driven BSDF representations are a critical part of this advance but pose new challenges in the area of device measurement and simulation. In this paper, we have shown how and why BSDF data are used in workflows related to daylighting analysis. Further adoption of these methods depends on extensive measurements and data sharing, which is a joint challenge for the research community, industry, and standards bodies. Research is needed to determine when and what type of measurements are needed; industry is needed for funding and access to samples and instrumentation, and standards bodies are needed to codify how data are to be shared and to define basic specification requirements.

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