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Simulating Complex Window Systems using BSDF Data

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ABSTRACT: Nowadays, virtual models are commonly used to evaluate the performance of conventional window systems. Complex fenestration systems can be difficult to simulate accurately not only because of their geometry but also because of their optical properties that scatter light in an unpredictable manner. Bi-directional Scattering Distribution Functions (BSDF) have recently been developed based on a mixture of measurements and modelling to characterize the optics of such systems. This paper describes the workflow needed to create then use these BSDF datasets in the Radiance lighting simulation software. Limited comparisons are made between visualizations produced using the standard ray-tracing method, the BSDF method, and that taken in a full-scale outdoor mockup.

Keywords: Daylighting, Design tools and methods

INTRODUCTION

Simulations enable designers and engineers to evaluate and select the best available window solutions for a particular building application. This study describes a new capability that enables designers to more accurately model the solar-optical performance of complex fenestration systems (CFS) such as Venetian blinds or daylight-redirecting prismatic louver systems. Due to a lack of detailed knowledge of directional optical properties, complex fenestration systems cannot be evaluated using conventional means. The Bi-directional Scattering Distribution Function (BSDF) expresses the way light is scattered by a surface and distributed for all incoming incident directions. So far, the number of tools that take advantage of BSDF data is limited.

The workflow described in this study starts with 1) measurement of the optical properties of the material that makes up the CFS, then 2) CFS layer and window system sub-modelling, then ends with 3) (indoor) space lighting simulations.

To incorporate BSDF data in the lighting simulations, the following software tools are sequentially employed:

- *TracePro* developed by the Lambda Research Corporation (Littleton, MA),
- *Window6* developed by the Windows and Daylighting Group of the Lawrence Berkeley National Laboratory (LBNL), then
- *Radiance* developed by the Windows and Daylighting Group of LBNL.

Two case studies of an office are presented with a window equipped with either an interior conventional matte-white Venetian blind (“matte-VB”) or an interior blind with complex, mirrored horizontal slats (“mirror-VB”, RETROLux blinds by Retrosolar).

OPTICAL MEASUREMENTS

There are a variety of ways BSDF data can be obtained for a material, depending on the properties of the material [1]. For these two cases, optical measurements were carried out at LBNL with the use of integrating sphere spectrophotometers to measure the direct hemispherical reflectance of the slat surface since the surface characteristics were largely Lambertian (perfectly diffuse) or specular. The integrating sphere collects all the scattered light that is transmitted or reflected from the studied sample, and a detector inside the sphere records the total value. Measurements are not envisioned to be conducted by the designer: in the future, material properties may be accessed through a database linked to *TracePro* or *Window6*.

SOFTWARE TOOLS

The purpose of the second step in the workflow is to first create a BSDF model for the CFS *layer* (e.g., interior shade), then combine the layer(s) into a complete framed window *system* (e.g., CFS shade + glass + frame). In the third step, this system BSDF model is then used in the daylight simulation of an interior space.

SUB-MODELING: LAYER SIMULATION

The BSDF of a CFS layer can be generated using either 1) a geometrical model of the layer (e.g., Venetian blind) combined with measured solar-optical data of the surface material in the ray-tracing *TracePro* software or 2) simplified geometric models of commonly-used shading systems (Venetian blinds, screens) with measured solar-optical data and radiosity calculations within *Window6*. The BSDF dataset generated with radiosity (forward solution of the light-energy equations) and raytracing (observer-based ray path) models show good relative agreement for Lambertian systems [2]. The choice of the most appropriate layer simulation method however depends on the complexity of the shading system geometry and material surface characteristics. Option 2 can be used only if the material characteristics are

Lambertian and the shading system is defined in *Window6*. With complex layer geometries and/or non-Lambertian surfaces, Option 1 must be used.

For the two cases modelled, different methods were used. The BSDF layer model for the matte-VB was created within *Window6* with flat slats using measured solar-optical data for the surfaces. For the mirror-VB which has a curved slat terminating in a series of “W”-like angles, an upper mirrored surface, and a matte-white under surface, the *TracePro* method was used, where the geometry was imported from a Computer-Aided Drafting (CAD) program. Reflectance properties were then assigned to each surface of this geometrical model, and then *TracePro* was used to generate a 145x145 BSDF matrix of incoming and outgoing transmittance and reflectance values for a specific slat angle.

SUB-MODELING: SYSTEM SIMULATION

In general, *Window6* is used to determine the thermal and solar-optical properties of complete window systems. To create a system in *Window6*, the CFS layer must first be imported (in the case of *TracePro*) or created (in the case of *Window6* method of layer definition) in the shading layer library. The window system is then built up by selecting the various layers that make up the window from the *Window6* library (e.g., CFS shade + air gap + glass layer + air + glass). *Window6* then generates an output BSDF file for the entire window system to be used in lighting and energy simulation software.

SPACE SIMULATION

Radiance, a lighting calculation and image-rendering program, consists of various tools that enable the user to create and render scenes. Space geometry is either modelled in *Radiance* or imported from CAD programs. After all scene files are created, the BSDF xml data are imported in *Radiance* through the newly-modified *mkillum* tool (version 3.9) in the illum layer scene file with the appropriate *mkillum* statement.

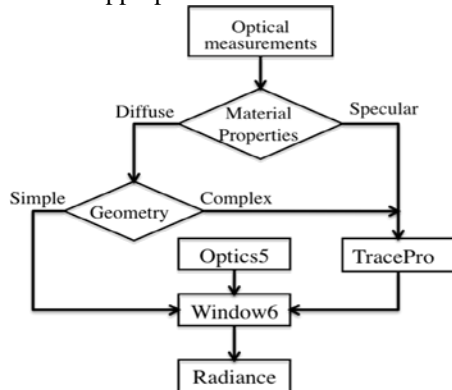


Figure 1. Process flowchart showing the software tools used to arrive at a photorealistic simulation of an interior space.

The entire workflow described in this study can be summarized in the flowchart shown in Figure 1.

EVALUATION OF A SIMPLE AND COMPLEX PROFILE SHADING SYSTEM

To examine the proposed evaluation process, the simple, matte-VB and complex mirror-VB shading systems were modelled and tested. Simulated images were generated using 1) the old “non-BSDF” *mkillum* tool (default backwards ray-tracing process + geometrical model of the shading layer and glass) and 2) the new *mkillum* model using BSDF system data. For comparisons between simulations and measured field data, the simulated space was made identical to full-scale, south-facing office test rooms in the Window Testbed Facility at LBNL, where energy and daylighting studies are performed. In this study, relative luminance distribution comparisons were made between simulations of the matte-VB and measured luminance data from calibrated high dynamic range (HDR) digital images, which were taken in the test room with the same shading system installed.

The LBNL test room, modelled in *Radiance*, is 3.05 m wide, 4.57 m long and 3.35 m high and the south-facing window is divided into an upper and lower zone. Inside the room are two workstations, a flat-screen computer monitor and an office chair. A desk lamp was also included in the model for visual interest. Reflectance and RGB values for the interior surfaces are given in Table 1.

Surface	R _{vis}	Red	Green	Blue
Walls	0.87	0.89	0.87	0.82
Floor	0.13	0.12	0.13	0.14
Ceiling	0.87	0.88	0.87	0.82

Table 1: Measured optical properties of surfaces in the test room.

Glass Layer	T _{sol}	T _{vis}	R _{sol-b}	R _{vis-b}
1: Low-e on ultra-white clear	0.416	0.676	0.469	0.211
2: Ultrawhite clear	0.867	0.902	0.076	0.081
Total Window	0.376	0.620	0.438	0.256

Table 2: Glazing and window system solar-optical properties

MATTE VENETIAN BLINDS

For the matte-VB system, the material reflectance was measured to be R=0.8 for both front and back surfaces. The slat material surface was diffusely Lambertian, not specular, therefore the shading layer was modelled directly in *Window6* as curved slats, as described above. First, optical properties were applied to the material and then the shading layer was created at the desired blind tilt (52°). The glazing system optical properties (Table 2) were imported from the LBNL *Optics5* computer program.

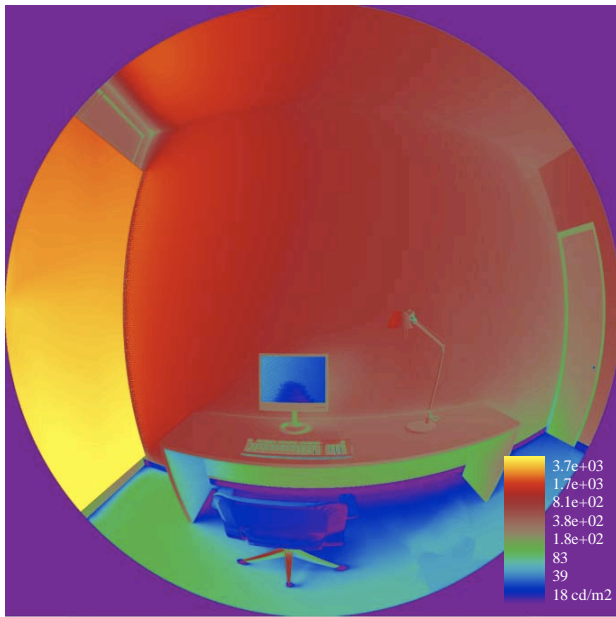


Figure 2a. Falsecolour luminance map (cd/m^2) rendered with the use of BSDF data. Matte-VB: January 15, 10:00 AM.

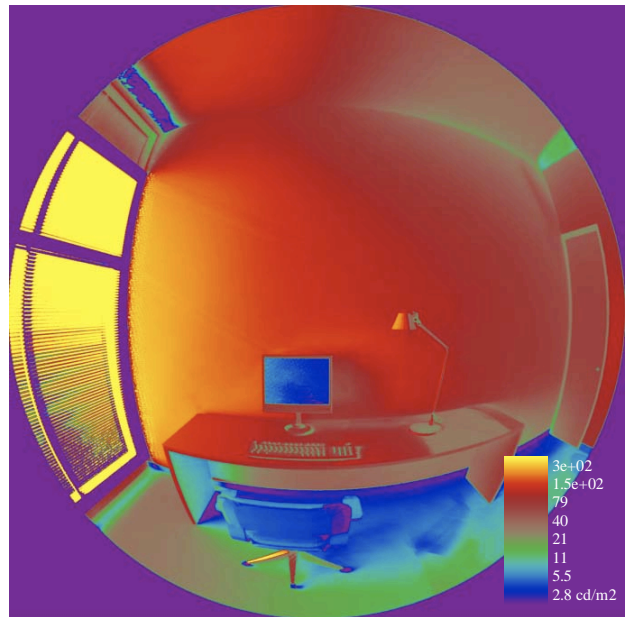


Figure 2c. Difference in luminance (cd/m^2) between Figure 2b and Figure 2a (nonBSDF - BSDF).

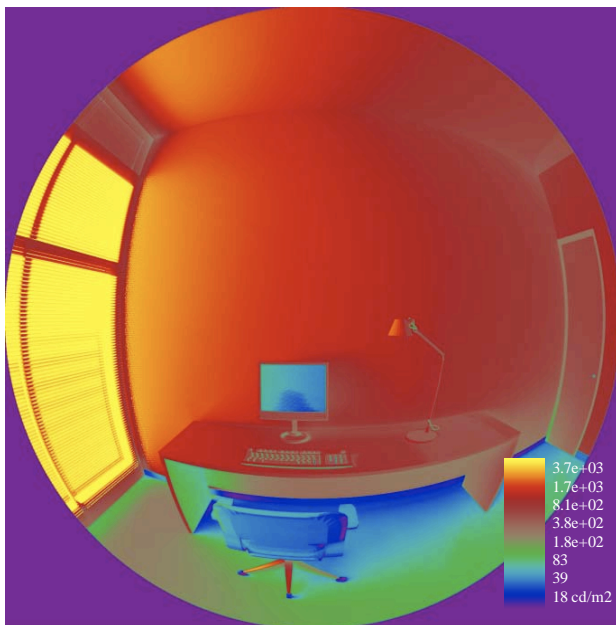


Figure 2b. Falsecolour luminance map (cd/m^2) rendered without use of BSDF data. Matte-VB: January 15, 10:00 AM.

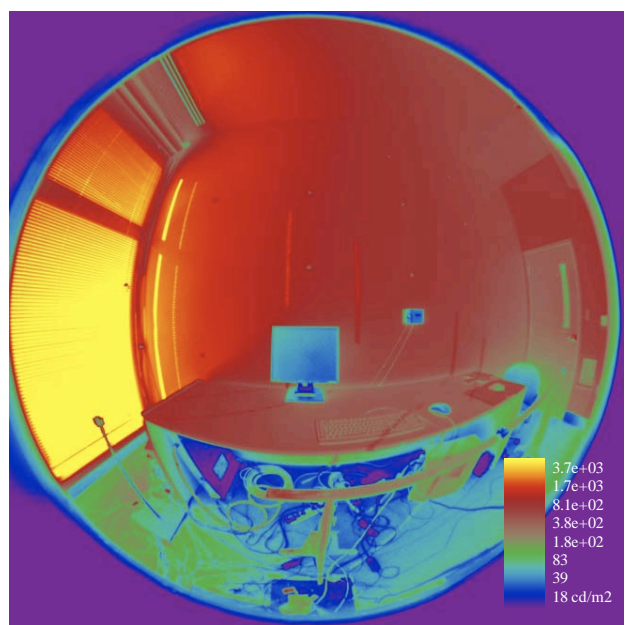


Figure 2d. HDR picture taken on the 01/15 at 10:00 AM in the test room.

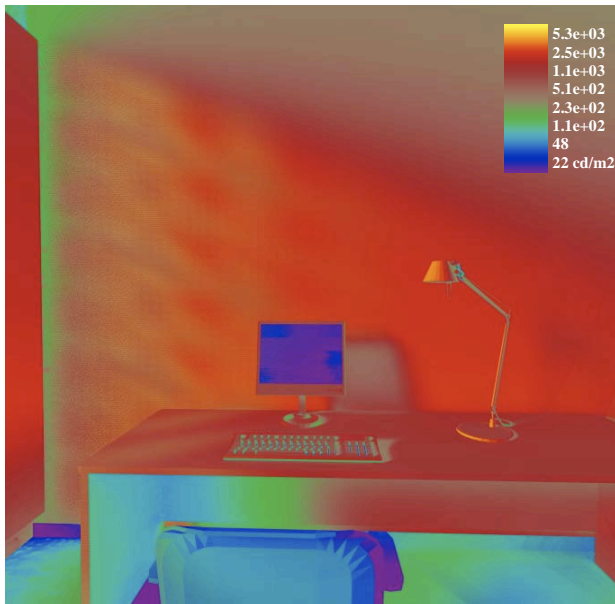


Figure 3a. Falsecolour luminance map (cd/m^2) rendered with the BSDF data. Mirror-VB, December 21, at 9:00 AM.

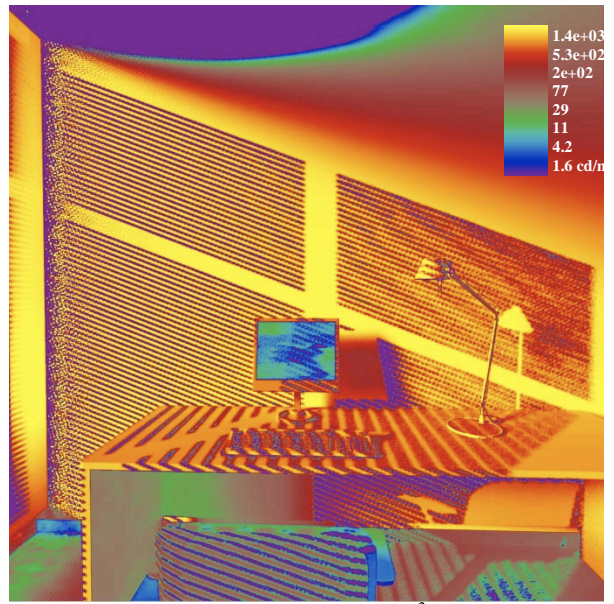


Figure 3c. Difference in luminance (cd/m^2) between Figure 3b and Figure 3a (nonBSDF - BSDF).

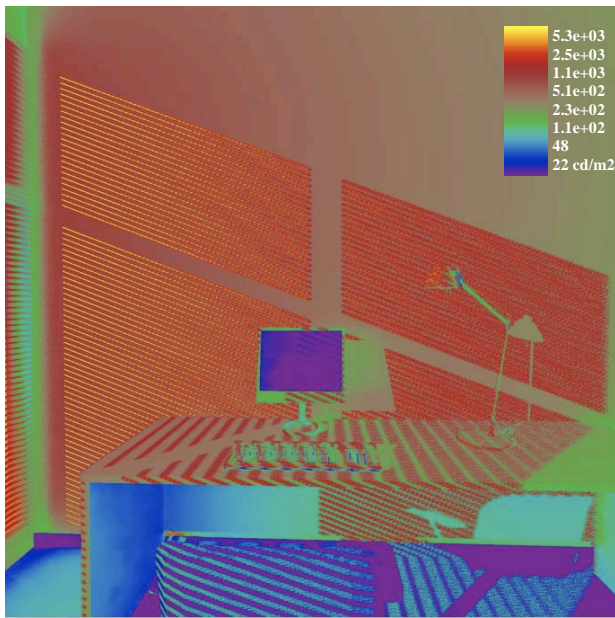


Figure 3b. Falsecolour luminance map (cd/m^2) rendered without BSDF data. Mirror-VB, December 21, at 9:00 AM.

Window6 then generated a matrix containing the BSDF (in xml format), which was then read by the *mkillum* tool in *Radiance*.

Rendering simulations using the new BSDF method (Fig 2a) and the non-BSDF, ray-tracing method (Fig 2b) were run for January 15th at 10:00 AM. To quantify the error between the two methods, pixel-by-pixel differences in luminance levels were calculated in *Matlab* (Mathworks, Natick, MA). Figure 2c shows this difference of the non-BSDF data minus the non-BSDF data as a falsecolor luminance map in cd/m^2 .

Interreflected daylight towards the back of the room were under-predicted by the BSDF method by 15-95 cd/m^2 maximum or 3.5-11%, while direct diffuse daylight on surfaces adjacent to the window were under-predicted by 95-220 cd/m^2 maximum or 5-11%. Differences may be caused by inaccuracies in the BSDF dataset or errors introduced by the interpolation and averaging routines within *mkillum* that translate the discrete 145x145 matrix of BSDF values to the time-specific sun position and sky condition of the modelled image. More detailed validation is currently underway.

Figure 2d shows the measured HDR luminance distribution, which differs substantially with the BSDF simulated values, due to differences in sky luminance and sky distribution, modelled interior and exterior conditions, and slight differences in location of view. Still, the luminance distribution is approximately similar with luminance ratios of surfaces being fairly constant across the width of the image: 1.74:1 next to the window, 1.08:1 in the center of the window wall to 1.15:1 towards

the rear of the room. Validation against physical measured data will occur after the validation activities using simulated data have been completed.

MIRRORED VENETIAN BLINDS

Due to the complexity of the slat geometry and its mirrored surface, ray-tracing *TracePro* program was used to generate the shading layer BSDF dataset. The shading layer was simulated in with a horizontal slat angle of 0° then the *TracePro*-generated BSDF data (in xml format) were imported in *Window6* (slat geometry is not needed in *Window6* if BSDF data are imported). The glazing system with the blind model was then solved in *Window6* to yield system-level BSDF data. As described above, the BSDF data were imported in *Radiance* and rendering simulations and calculations were performed (Figures 3a-c).

The distinct slat shadow lines shown in the non-BSDF rendered image (Fig 3b) are not seen in the BSDF image (Fig 3a) because this current version of *mkillum* uses the BSDF input without a geometrical description of the shading system assigned to the window. The interior luminance levels given in the BSDF image are accurate if one compares the average value across an area that includes several periods of sunlit and shadowed areas produced by the slats. The *mkillum* tool can accept a geometrical description of the optical system so that the rendered image will look similar to the ray-traced image but this feature has not yet been validated.

In this comparison, the non-BSDF image is likely to be less accurate than the BSDF image because the slat has a mirrored surface and a unique slat profile. The “mirror” material type in *Radiance* can produce the secondary source reflectance of mirrored surfaces but the calculation is inefficient and unlikely to converge since the backwards ray-tracing method must find then image the solar disk for each individual slat (i.e., the Monte Carlo random sampling algorithm may or may not find the sun). For these simulations, the large u-curve of the slat was modelled as a mirror and the w-shape at the tail of the slat was modelled as a metal material to avoid an interminable calculation time. The BSDF method has the advantage both in terms of accuracy and calculation speed because these reflections are taken into account in the base BSDF input file to *Radiance*.

Because the BSDF method accounts for the direct component of reflected sunlight, all luminance levels in its image are greater than the non-BSDF image by a significant amount. Assuming in this case that the BSDF values are more correct than the ray-tracing method, we found that the ray-tracing method under-predicted luminance levels on the wall in the center of the room by 60 cd/m^2 or 3.1%, while the surfaces adjacent to the window were under-predicted by 685 cd/m^2 or 35% for

this low-angle solar condition (December 21). Note that again, the BSDF image does not render the distinct light and shadow pattern of the horizontal slats. In Figure 3a, indistinct patches of reflected daylight on the wall adjacent to the window may be attributed to reflected sunlight off the surface of the mirrored slats.

CONCLUSIONS

A new method of simulating complex fenestration systems has been described that will enable greater accuracy at significantly lower computation times compared to traditional ray-tracing methods. Complex fenestration systems such as Venetian blinds and louvers create problems for default ray-tracing techniques when computing interreflections particularly for specular mirrored surfaces, requiring excessive computation time for reasonable convergence. The new *mkillum* tool provides a means for *Radiance* users to improve their results by precalculating an output distribution for such systems and treating them as light sources in the subsequent rendering phase.

The full workflow was described, from creation of the layer BSDF to system BSDF then use in the *Radiance* simulation tool. Other programs such as the *DeLight* module in *EnergyPlus* [5] also use BSDF data for more accurate prediction of daylighting quantities. Work has also been initiated at LBNL to use BSDF data in solar-optical computations in *EnergyPlus* to more accurately quantify the heating and cooling load impacts CFS systems have on buildings.

Comparisons between data produced using traditional ray-tracing versus BSDF methods show good relative agreement, although this limited “validation” exercise has by no means vetted the tools. Further validation is planned in future work.

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