Goniophotometry and assessment of bidirectional photometric properties of complex fenestration systems

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Abstract

This paper seeks to provide an overview of the currently available assessment tools for Bidirectional Transmission or Reflection Distribution Functions (BTDFs, BRDFs) of complex fenestration systems (CFS). In the first part of the paper, the existing experimental devices (goniophotometers) developed specifically for CFS measurement are described. All but two are based on a scanning process to investigate the emerging light flux distribution, the alternative approach being based on digital imaging techniques. A critical analysis of their advantages and shortcomings is proposed to provide both researchers interested in replicating them and more generally potential users of BTDF or BRDF data with a lucid idea of the available options.

The second part presents an alternative to physical measurements, made possible by using computer simulations based on ray-tracing techniques. In this case, every component of the modelled system must be of well-known geometric and material properties. Three virtual goniophotometer models are described and their validation results are analyzed.

Whether they have been generated experimentally or through simulation, BTDF and BRDF data need to be processed into transmission or reflection functions that are directly related to sky and room conditions for them to be usable. The third part of the paper introduces a new BT(R)DF database management system whose aim is to become a reference resource for viewing and interpreting these complex data. The main visualization features of its interface are presented, that include a special focus on flexibility and on providing intuitive graphical information, in a similar way as for luminaires selection in electric lighting design.

Key words: Bidirectional Transmission (Reflection) Distribution Function (BTDF, BRDF), Goniophotometer, Ray-tracing, Daylighting simulation tool,

1 Introduction

To allow an efficient integration of complex fenestration systems (CFS) in buildings, a detailed knowledge of their directional optical properties is necessary. The latter are described by Bidirectional Transmission (or Reflection) Distribution Functions, abbreviated BT(or R)DF, that express the emerging light distribution for a given incident direction [1]. Having access to such detailed transmission or reflection functions will help manufacturers to develop and optimize their products and architects in selecting the latter judiciously already at the project's level [2, 3]. It will also help daylighting simulation tool designers to improve their programs' performances [4, 5, 6, 7, 8] and achieve a reliable modelling of light propagation into rooms using CFS.

A serious effort has been made in developing accurate and efficient bidirectional goniophotometric devices for detailed studies of such systems, capable of measuring BTDFs and/or BRDFs in an appropriate way. The existing instruments are described in this paper [1], the vast majority being based on a scanning process (i.e. on relative individual movements of the detector) and a couple being based on a different approach, that relies on digital imaging techniques for detection. The advantages and shortcomings of each approach are analyzed. For each of the experimental devices developed for CFS, the adopted validation method and estimated accuracy on BT(R)DF data are then given, whenever documented in publications, together with a list of characterized systems and available bidirectional data today.

The second part of this paper focuses on virtual goniophotometers that have been developed, mainly based on commercial forward ray-tracing simulation tools and allowing to complement experimental assessment in a very efficient way. Indeed, such techniques allow more flexibility in parametric studies, and the performances expected for variants (in geometry, material) of a same system can be more easily tested as long as all the parameters are known. The different existing simulation models are described, together with the validation methods or comparisons that were used. A list of available bidirectional datasets based on ray-tracing techniques is also provided.

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[1] A more extensive review is given in [9].

The light transmittance through complex fenestration systems (CFS) is by definition angular-dependent. Therefore, the indoor light penetration scheme strongly depends on the overall outside illumination conditions as well as on the time and space conditions. These dependencies have to be handled easily by the designer to help him find appropriate solutions to a given problem. For this purpose, a flexible user-interface is introduced for BT(R)DF data in the third part of the paper. This software aims at providing a quality-controlled support for CFS database management comparable to programs developed for luminaire selection in artificial lighting design [10, 11]. As BT(R)DF data require both a sophisticated assessment equipment and expertise in data interpretation, having them gathered in one flexible database management and visualization system will allow them to be more widely used and understood.

2 The Bidirectional Distribution Function

The Bidirectional Transmission (or Reflection) Distribution Function, abbreviated BT(R)DF, is defined by the Commission Internationale de l'Eclairage [1] as "quotient of the luminance of the medium by the illuminance on the medium". It is therefore angle-dependent at both the incidence and the emergence levels and expresses the emerging light flux distribution for a given incident direction.

Generated BTDF or BRDF data files follow a common format defined within the Task 21 of the International Energy Agency [5], based on the subdivision of the sky hemisphere into 145 sectors [12] that determine a default set of 145 incident angles. To represent bidirectional functions graphically, so-called photometric solids are often used, that consist of plotting the BT(R)DF data in spherical coordinates [13], as illustrated in Figures 1(a) and 1(b) for transmission and reflection figures respectively.

Fig. 1. BTDF and BRDF representations as photometric solids for the sun-directing glass "Lumitop^{TM}" and a Holographic Optical Element (source: [9]).

¿From a complete BT(R)DF dataset, it is possible to determine the directional-hemispherical visible transmittance τ_{dh} or reflectance ρ_{dh} by approximating the integral over the whole collecting hemisphere with a sum over all individual BT(R)DF data [5, 9]. This parameter is of great importance in the validation of bidirectional measurements, as it can be compared to measurements performed on the same material with an integrating (Ulbricht) sphere [14]. It is also critical in the assessment of the global photometric behaviour of a fenestration material.

3 Experimental methods for goniophotometric assessment

The range of applications for bidirectional goniophotometers has broadened increasingly since the early nineties, especially with the strong progress made in computer graphics rendering, for which various devices have been developed specifically [15, 16, 17]. These applications also include analyzing luminaires and lamps [18, 19, 20, 21], and characterizing ground surfaces [22, 23, 24] or surface textures [25, 26, 27, 28]. Amongst the latter group, Dana's paper [28] should be pointed out as it is where a BRDF with spatially-varying reflectance over the sample surface was first defined as "BTF" for "Bidirectional Texture Function".

A serious effort has been made as well in developing accurate and efficient bidirectional goniophotometric devices for detailed studies of fenestration systems, capable of measuring BTDFs and/or BRDFs in an appropriate way for such materials, and this is the category the present paper is focusing on.

These devices are almost all based on a scanning process (see Section 3.1), i.e. on relative individual movements of the sample, detector, and/or source to monitor all incoming and outgoing light flux directions for which BT(R)DF data are needed. Some, however, propose a way to reduce this onerous scanning process by adopting a video-based approach (Section 3.2), and rely on the detection of light through digital video capture after being collected on a device-specific projection surface.

Independently of the investigation method (scanning or video-based), a goniophotometer that does not analyze the spatial variation of BTDF or BRDF over the material itself (that does not produce "BTF" values [28]), will average this variation over the sample's investigated area, except if it is able to isolate a given direction of emission from a larger sample area, as for the instrument developed at Cardiff University [29], described below. In any other case, it will assume that light collected on the detecting surface (the photo-sensor's surface or the pixel) comes from a point (or an infinitesimal surface), even though rays emitted from the edges of the sample's investigated area could typically also reach the detecting surface by following a slightly different direction.

In consequence, the detection surface should be able to encompass the possible divergence of the rays that reach it, which is inversely proportional to the sample's investigated area. This can be achieved by either choosing a sensor element of appropriate dimensions, or, if the detector is too small or too close for the investigated sample area, by defining averaging sectors of extent comparable to the emitted rays' spread.

If this averaging is not applied properly (within an appropriately-sized angu-

lar sector considering the sample's investigated area), BT(R)DF data become inconsistent as they will associate luminance values to specific directions despite the possible spread of rays around these directions. Data obtained for a same material might then differ greatly depending on the exact sensing area and position (unless the investigated material presents perfectly diffusing properties).

The draw-back of this averaging is that, especially for large sample areas (thus large angular sectors), narrow luminance peaks in a BT(R)DF will not be preserved, as they will be averaged with the surrounding light distribution. This might make local (but possibly important) issues in visual comfort and glare difficult to reveal. The only way to preserve these peaks while keeping a large investigated sample area would be to isolate emerging directions accurately [29] or measure BTFs [28].

3.1 Characterization based on a scanning process

3.1.1 Pros and Cons

The two main draw-backs of the scanning approach are the considerable measurement time needed for a BT(R)DF assessment (the finer the angular resolution, the longer the procedure), and more importantly the fact that the investigation is discrete. A preliminary scanning is thus required for every incident direction to locate luminous "peaks" and assess the general transmission and/or reflection properties of the material beforehand - lengthening the overall procedure even more -, while the risk of missing some significant feature between two measurement points can never be avoided completely.

Especially for materials presenting high dynamical luminance ranges, local refinements of the angular resolution will be necessary for the final scanning so that interpolation between discrete data points remains reliable. Apart from requiring even more time to perform the measurement, these refinements make it more difficult for simulation programs to implement the BT(R)DF data afterwards. In addition, the estimation of the global (directional-hemispherical) transmittance or reflectance becomes delicate, as a weighing of data is then necessary, based on the areas associated to each point; these areas are however difficult to determine as they are distributed irregularly[30].

In most cases, the type of photo-sensor chosen in a scanning approach makes it relatively easy to deduce BT(R)DF values based on the sensor's output (voltage, illuminance, luminance). This approach is therefore often more appealing to someone wanting to construct such an instrument and get it operational quickly. Finally, for experimental set-ups such as the Cardiff goniospectrome-

ter [29], the scanning approach can present the important advantage of being able to accurately determine the emerging light distribution's directionality. This is discussed in the next section where this device is described.

3.1.2 Existing scanning-based goniophotometers for CFS: innovations and validation results

The first goniophotometer ever developed for BT(R)DF measurements of fenestration materials was made at the *Lawrence Berkeley National Laboratory (LBNL)*, USA in the late eighties [31]. Achieved BTDFs were used to predict the performances of multi-layer fenestration systems, and were implemented in matrix-layer calculations to validate this analytical approach against measured solar heat gain values (g-values) [32, 33, 34].Comparisons showed that calculated and measured SHGC data were matching to within 10% except for grazing incident angles, which was considered highly satisfactory considering the many parameters involved.

An attempt of comparing BTDFs to ray-tracing calculations was made later but proved unsuccessful, the discrepancies between measurements and simulations remaining very important from both the quantitative and qualitative points of view [35].

At the *Fraunhofer Institute for Solar Energy Systems (ISE)*, Freiburg, Germany, Apian-Bennewitz [36, 37] designed a goniophotometer allowing the sample dimensions to be flexible, which was an innovation in regard to LBNL's device. This device was also the first one to apply adaptive refinements in angular resolution (at the unavoidable expense of a longer, two-steps investigation process) and the first one for which bidirectional results were integrated and validated against Ulbricht integrating sphere measurements. These comparisons showed discrepancies of about 20% in general [2]. In addition to this, a comparative study was made with ray-tracing simulations [38] on polymers and aerogels; directional-hemispherical transmittance comparisons here showed only 5% disagreement for small incident angles, increasing to 61% beyond 60°. An upgrade of this device is under way at ISE, with an improved light source and a calibrated and movable CCD camera as the detector to identify details on the surface of façade elements. No publication is yet available on the achieved or expected accuracy of the system, or its validation.

The optical consultancy company *pab®-opto* [39] now proposes a new goniophotometer design with a detector fixed on an articulated arm moving around the sample (for both BTDF and BRDF measurements). This apparatus is meant to be mainly used in-house for project work and consulting jobs, but

[2] Approximate value based on reading the comparison graph provided in [37].

the goniophotometer is also available as a custom build turn-key system. One of its major innovations lies in the variety of light sources that can be used (Xenon, Halogen, laser), and in its modular concept for detection (silicon, pyroelectric, thermopile covering various spectral ranges).

Another goniophotometer based on a scanning process and proposing laser beams as a possible light source was realized at the *University of Technology Sydney (UTS)*, Australia [40, 41]. Its mechanical concept is close to the one found at ISE. No validation results could be found in the literature.

At the *Berlin University of Technology (TUB)*, Germany, a former, spiral scanning design [42] is now being replaced by a new approach including a rotating arc and multiple sensors. No measurements have been published yet with this new design.

At the *TNO Building and Construction Research*, Delft, The Netherlands, a goniophotometer of design very similar to the initial version of ISE's apparatus [36] has been developed [43, 44]. It was at first meant for characterizing transparent-insulating (TI) materials; in 2000, it was adjusted to measure other systems as well like simple and complex glazing, plastics and shading fabrics. Its validation was again based on integrating sphere measurements comparisons, that led to relative discrepancies generally of 10% (20% for a few samples), except for particularly low transmittance values where discrepancies increased drastically [44].

At *Cardiff University*, UK, Breitenbach and Rosenfeld [29] proposed a major innovation in goniophotometry by adding spectral analysis capabilities. These have the important advantage of making the assessment of wavelength-selective glazings possible. In addition, a light detection system consisting of an off-axis parabolic mirror focuses the transmitted light onto the end of an optical fiber bundle that limits its possible divergence around a given direction to about $\pm 0.5°$. Hence, this set-up is able to achieve a high directional accuracy while keeping a large investigated sample area, unlike any other approach (including video-based). This technique has in fact been recently adopted at TNO as well. Cardiff's device is now owned by the *Technical University of Denmark (DTU)*.

Directional-hemispherical transmittance values based on BTDF integration were here again compared to integrating sphere results [29], but also to analytic model predictions [45, 46]. The error on goniospectrometric data was estimated to be of about 11% [3].

[3] Based on error bars and discussion found in references [45, 29, 46].

The main features of these devices are summarized in Table 1, together with those relying on digital imaging.

3.2 Characterization using digital video techniques combined with a projection principle

The use of Charge-Coupled Device (CCD) cameras allows one to achieve a fine investigation of the materials while maintaining an appreciable flexibility and time-efficiency in data acquisition and processing. One of its greatest advantages is to allow the visualization of many directions or locations at the same time. Examples of video-photometers and mapping luminance-meters resorting to digital imaging are numerous [47, 48, 49, 50, 51, 52].

To avoid having to move from one acquisition position to the next one with a CCD camera, this image-based detection can be combined with a projection principle.

3.2.1 Pros and cons

Choosing to point an imaging detector towards a projection surface to assess BT(R)DFs allows time-efficiency to be tremendously improved compared to a scanning approach as a single digital image will cover thousands of emerging directions. This major advantage is combined with an even more important one pertaining to the reliability of measured data: the information is continuous and the collection hemisphere is fully covered, as there is no gap in the pixel mapping of the captured images. This ensures that no feature can be missed, as each pixel represents an average of the light distribution detected within its area and is adjacent to its neighbor.

The only parameter that limits the angular resolution is the pixels size, which nowadays has stopped to be a constraint: indeed, even very narrow luminance peaks due to small heterogeneities of the material (like a perforation e.g.) are likely to be larger than the solid angle covered by one pixel. However, it must be kept in mind that for any approach that does not isolate specific directions of emission (whether using a scanning or a video-based method), an averaging into sample-dependent angular sectors is necessary to produce consistent BT(R)DF data. Because information is continuous, this averaging is actually more reliable with digital imaging than point-per-point scanning, as no interpolation is required.

By capturing several images of the same luminous situation at different integration intervals, large dynamics in luminance can be assessed with constant accuracy, and saturation or under-exposure effects can be prevented.

The major difficulty in this approach lies in the complex and numerous calibration procedures needed before the instrument is operational [9], and the data reliability and accuracy will depend on their careful execution.

3.2.2 Existing video-goniophotometers for CFS: innovations and validation results

Four instruments based on this alternative method exist today, and only two were designed for CFS: the first of the four, developed at the *Lawrence Berkeley National Laboratory* [53] for computer graphics applications, inspired two more recent designs. One at the *Université de Rennes 1*, in France [54], to enhance photo-realistic rendering, and the other at the *Massachusetts Institute of Technology (MIT)* [55], still under development for the characterization of CFS and light-redirecting materials. It aims at being able to provide not only photometric functions but also the spectral properties of transmitted and reflected light to enable selective glazing analyzes. Its other major innovation is to extend the wavelength range to the near-infrared in order to incorporate thermal issues as well.

All three rely on the use of a CCD camera equipped with a fish-eye lens to collect the light emerging from the sample after being reflected on either a specular (semi-transparent hemisphere [53] or ellipsoid [55]) or a diffuse (cube [54]) surface. These variants of the same, fish-eye camera approach, reduce the measurement time to its minimum: a quasi-instantaneous assessment of the full light distribution in reflection or transmission.

At the *Solar Energy and Building Physics Laboratory (LESO-PB)* of the *Swiss Federal Institute of Technology (EPFL)*, a different design was realized using a CCD camera with a wide-angle lens aimed at a triangular and diffusing projection screen [56, 57]. The latter collects the light emerging from the sample and rotates around it to cover the full 2π steradian hemisphere. A procedure is completed after 6 screen positions separated by 60°, which makes this approach slightly less time-efficient than the previous ones but still considerably more than any scanning-based method.

This device distinguishes itself from all the other goniophotometers for CFS so far in how extensively its results were validated [58]:

- assessment of error at each intermediate stage of calibration and processing, a final relative error of 10% being deduced;
- bidirectional measurements of systems presenting a known symmetry and verification against standard luminance-meter data or analytical calcula-

tions (1.5% to 8% errors);

- empirical validation based on bidirectional measurements comparisons between different devices (5% to 8% differences);
- comparison to Ulbricht sphere measurements (6% to 14% variations);
- comparison of monitored data with ray-tracing simulations to achieve a higher level of details in the BT(R)DF behavior assessment (discrepancies always lower than simulation model errors [59, 60]).

3.3 Summary of current goniophotometer designs and available datasets

Table 1 summarizes the main features of the different instruments developed for advanced fenestration systems: research institute, measurement type, detection hemisphere coverage, directional accuracy, spectral analysis capabilities, measurement time, validation method and estimated accuracy, and device reproducibility, i.e. how easy it would be to make a replica of these devices.

This feature is outlined in as an emoticon, mainly based on how difficult it would be to reproduce the calibration procedures. Devices using CCD cameras as light detectors (new device at ISE, devices at EPFL and MIT) definitely fall in the "not easy to replicate" category, while pab®-opto's device, typically, is meant to be easily reproduced.

Table. 1. Main features of current bidirectional goniophotometer designs for the experimental assessment of façade components and fenestration systems.

As explained in the introduction part of Section 3, the directional accuracy ("Direc" in Table 1) is generally determined by the sample's investigated area ("sample"), i.e. by the area of the sample that is either viewed by the photo-sensor in a scanning approach or that is emitting light in a video-based approach. The only two exceptions are DTU's (formerly Cardiff's) and now TNO's devices that offer a much better directional accuracy while keeping large sample areas, as mentioned in Section 3.1, in addition to ISE's device that will provide BTF's.

The measurement time per incident direction is rarely stated explicitly in publications for scanning-based devices, as it varies strongly with angular resolution. Based on discussions with several people working with such devices, typical procedures tend to require between 10 minutes and several hours for one incident direction, depending on the resolution chosen. Reference [29] mentions 5 to 10 hours but this is largely due to the additional spectral scans performed at each position. Monitoring times of 40 minutes per incident direction for scanning-based goniophotometers were therefore assumed when calculating the total measurement times in Table 1, unless other monitoring times were indicated in the literature. The total time estimations are based on a full

BTDF or BRDF characterization, which, by default, comprises 145 incident directions to investigate (in case the sample presents no symmetry). This leads to tremendous monitoring times for scanning-based approaches and is one of the reasons extensive BTDF and BRDF databases are still rare.

Table 2 presents an overview of the measured BT(R)DF datasets available today for Complex Fenestration Systems (CFS), grouped by type. The table provides the usual name of the prototype, its symmetry indicator (0 if no symmetry, 1 if rotational symmetry, 2 if symmetry to $\phi = 0° - 180°$ axis, 3 if symmetry to $\phi = 90° - 270°$ axis, 4 if symmetry to both $\phi = 0° - 180°$ and $\phi = 90° - 270°$ axes), the number of incident directions that were investigated and the institute that performed the measurements. As can be seen, EPFL [9] offers the largest one available today, with 37 characterized systems amongst which 6 were fully characterized (incident directions set based on the default 145 directions, but reduced accounting for symmetries). Published BT(R)DF data measured in a systematic way (beyond calibration or validation purposes) also include 5 materials measured at TNO along 3 incident directions each [44], and two, resp. one, fully characterized systems measured by TUB, resp. ISE [5].

Table. 2. Overview of the measured BT(R)DF datasets generated at LESO-PB/EPFL, TNO, TUB and ISE (physical goniophotometers): *B.-H. stands for Baumann-Hüppe AG; **x 3 relates to the 3 slats configurations that were considered for each blind: 0°, 45° and 90°).

4 Assessment of bidirectional distribution functions using numeric methods

Ray-tracing simulations provide a useful tool for evaluating complex systems in full detail. Outside of BT(R)DF and CFS characterization, many assessment methods for the optical performances of glazing or shading systems have resorted to comparisons with ray-tracing simulations:

- to establish a set of quantity and quality criteria for advanced daylight systems and determine their performances with *Radiance* simulations [61];
- to test a new ray-tracing approach for thermal radiation [62] or prismatic panel performances [63];
- to develop an angle-dependent evaluation procedure of solar heat gain coefficient (g-value) and compare measurements to ray-tracing simulations carried out with the software OptiCAD® [4] [64, 65];

[4] Opticad Corporation.

- to determine the daylight distribution in a room and compare *Radiance* simulations with office room monitoring [66].

Three virtual goniophotometers have been realized based on ray-tracing calculations. Two of them are described in more detail below. The third one was developed based on an extension of the Genelux lighting simulation software [67]. A detection hemisphere was generated on either side of a virtual sample to record BRDF (incidence side) and BTDF (emitting side) data. Preliminary results were obtained with a lambertian diffusor, a glazing panel and several venetian blinds with planar slats but no published material could be found that described this approach further and validated its results. This numerical goniophotometer is therefore not discussed in more detail in this paper.

The main advantages of simulation-based approaches in goniophotometry are to increase flexibility and often cost-effectiveness greatly compared to experimental approaches. Their main draw-back is that all properties of each and every component (geometry, material) need to be known in advance, which often still requires measurements. Where they become most useful is when several configurations of a same system are to be assessed, made out of individual components of known properties, or to evaluate and optimize the performances of products at an early design stage (before a prototype is made).

4.1 LESO-PB/EPFL virtual goniophotometer using TracePro®

The experimental conditions for the LESO-PB/EPFL instrument [57] were reproduced virtually with the commercial forward ray-tracer TracePro® [5] that is based on Monte Carlo calculations. Computer simulation results were then compared to BTDF data assessed with the experimental goniophotometer.

The properties of this numerical goniophotometer are described extensively in [59, 60]; the resulting simulation model for a 5° by 5° grid is shown on Figure 2 with a laser cut panel as the investigated sample.

Fig. 2. Simulation model composed of an opaque diaphragm, the analyzed sample, a non-interacting incident flux detection surface and six absorbing detection screens split into adjacent angular sectors.

This model was used to analyze prismatic panels, a laser cut panel, a Serraglaze™ panel and mirrored venetian blind prototypes manufactured by Baumann-Hüppe AG.

[5] Lambda Research Corporation, Inc.

Detailed comparisons with measured BTDF data were conducted, and led to discrepancies varying between 5% and 25%, that were checked to be always inferior to the estimated errors due to the ray-tracing method itself [59, 60].

To complement this study, an additional analysis made possible by the flexibility of virtual models was carried out. The idea was to assess the extent to which mechanical and equipment constraints applicable to the original, physical instrument (described in Section 3.2) altered the accuracy of measured BT(R)DF data. Therefore, an ideal set-up was modelled with a virtual sun as the light source and a hemispherical detector [59], shown in Figure 3 with a ray-tracing plot for an asymmetric prismatic panel manufactured by Siemens AG. As a matter of fact, it was found that the assumptions made for the construction of the instrument were good, and that the results obtained for the ideal model and actual set-up differed by less than 11% in relative terms.

Fig. 3. Ideal set-up model configuration: hemispherical absorbing detector and virtual sun.

4.2 FHG-IBP numerical goniophotometer environment using OptiCad®

The FHG-IBP numerical goniophotometer is based on the commercial forward ray-tracing tool OptiCad®[68].

Unlike the LESO-PB/EPFL virtual goniophotometer, this model does not try to reproduce a specific (physical) goniophotometer. As depicted in Figure 4, sensor planes that record the flux coming from the sample are arranged as a hemicube, since the program OptiCad®provides planar sensors only. From the flux received on the individual patches and the relative geometric position of the the latter with respect to the sample, both BTDF and BRDF values can be calculated [69, 70].

Fig. 4. Illustration of FHG-IBP numerical goniophotometer. The flux detected on the sensor planes of the hemicube is converted into luminance coefficients (BTDF values).

The set-up parameters such as the distance between the sample and each sensor plane or the subdivision of sensor planes into adjacent patches all affect the angular resolution and can be user-defined. For instance, angular resolutions (averaging intervals) of about 4° can be obtained with a hemicubic arrangement of sensor planes in roughly 5,000 patches, while a 2° resolution would require 20,000 patches.

The adjustable distance between sample and sensor plane also keeps errors due to flux recordings in the photometric near-field under control. For a given maximum error on BTDF or BRDF data, shorter distances between sample

and sensor planes can typically be accepted if the sample is diffuse (scattering), whereas for samples showing highly directional (spiky) properties, larger distances are required if the same error is to be maintained.

As an example Figure 4(a) illustrates the flux received from venetian blinds with slats tilts 0° and 40°, illuminated by a virtual light source from a 60° angle. The slats have a mirror coating on the concave side. In Figure 4(b), normalized BTDFs at slat inclinations 0° are depicted for 10,000 and 1,000,000 traced rays. Results were validated against analytical and measured reference cases (diffuse,standard and prismatic glazing, laser-cut panel) [70]. Obtained error ranges were similar to the ones determined for LESO-PB/EPFL virtual goniophotometer introduced earlier (relative errors ranging from 5% to 25%).

Fig. 5. Flowchart illustrating the program interaction and dataflow of the FHG-IBP numerical goniophotometer environment.

As depicted in Figure 5, the numerical goniophotometer is embedded into a semi-automated environment allowing the user to:

- configure a virtual set-up,
- parameterize and combine CFS samples,
- postprocess data for further use in daylight simulation.

To generate the required OptiCad®code automatically, a CFS Sample-Generator is provided. Different combinations of CFS components can be arranged in layer structures. The specification of the components and of the layer structure is supported by a graphical user interface. A postprocessor that implements calculated BTDF data into daylighting simulation tools is also included in the virtual goniophotometer environment, as described in the following section. This environment therefore aims at providing a close interface between the BTDF determination process itself and the process of daylight simulation and design. Table 3 gives a selection of the samples currently available, with a listing of the key configuration parameters.

Table. 3. Selection of CFS-models currently supported by the FHG-IBP CFS-Sample Generator with key configuration parameters.

4.3 Available datasets

Table 4 shows a selection of simulated BTDF datasets. For use in daylight simulations (see Section 5), a system's BTDF data have to be available for 145 incident angles, this set being reduced if the sample presents known symmetries [5].

Table. 4. Overview of the computed BTDF datasets generated at LESO-PB/EPFL and FHG-IBP (numerical goniophotometers): * according to the manufacturer's specifications, calculated for different slat inclinations from *system open* to *system closed*; ** calculated for 15 incident directions at slat tilts 0°and 45°.

5 Incorporation of CFS datasets into daylight design practice

Compared to standard glazing systems, the presence of one or more CFS in a façade makes it much more complex to determine what the spatial and time variant indoor lighting conditions will be. Indeed, not only will they depend on the outside illuminance conditions but also on the CFS' specific bidirectional light transmittance function, that is defined for each possible incoming light direction.

These dependencies have to be made transparent to the designer in an easy-to-handle way, such that for a specific problem, the best solution can be identified at low expenses. This requires CFS data to be included in (day-)lighting design tools so that a system's performance can be simulated under different skies for arbitrary room and façade conditions (geometry, surface reflectance). On the other hand, an appropriately managed database can offer quick pre-simulation support in the selection of suitable CFS, in a similar way as in a luminaire selection process in artificial lighting programs.

To make the BT(R)DF data diffusion more efficient, it also seems essential to gather these data into as few databases as possible, updated as more data become available.

5.1 Data processing and inclusion into lighting design tools

Based on the outside luminance distribution and the BTDF data provided, the luminous intensity distribution on the inward facing side of a CFS element is calculated [7]. In this method the BTDF data are to be properly interpolated and superimposed first. The luminous intensity distributions are then integrated into radiosity or ray-tracing based lighting calculation engines to determine the indoor illuminance conditions. The method has been validated, differing compared to the reference cases between 2% and 12% in relative terms, depending on the type of BTDF data and outside luminance distribution considered. Figure 6 shows a photo-realistic visualization of a daylit room using a light redirecting glass in the upper part of a window, modelled as a light emitting surface of given luminous intensity distribution. The calculation has been performed for March 21st at noon at the location Stuttgart for

a south facing facade.

Fig. 6. Photo-realistic visualization of room illuminated by standard venetian blinds in the lower façade area and a light redirecting glass in the upper façade area.

5.2 Graphical User Interface assessing a system data base

A graphical user-interface based on a database holding BTDF datasets of different CFS allows to identify a suited CFS solution for specific problems at low expenses. Several of the CFS's characteristics can be viewed, including:

- *System Information:* Graphics, pictures, and literature about specific systems, and case studies showing applications of such systems in real and simulated environments.
- *Display of the raw data files:* Display and analysis of the BTDF data and directional hemispherical transmissions.
- *Sky Luminance Distributions:* Display of CIE sky luminance distributions for different façade orientations and tilt angles, including direct sun interaction for static and dynamic systems.
- *Light emitting surfaces:* Calculation and display of light distribution through the façade system (similarly to candlepower distributions in artificial lighting).
- *Room illumination:* Simple ("shoe-box" type) room visualization for different outside illumination conditions.

The provided functionalities "Light emitting surfaces" and "Room illumination" are incorporating the method mentioned in the previous section [7]. Illumination within the room itself is calculated using a simple radiosity algorithm. The system runs under MS-Windows™ operating systems. Being based on COM-technology [71] it enables an easy data exchange and integration with third party software. Further information is available under *www.talisys.de*. For inclusion of additional BTDF datasets and for inclusion of the graphical-user interface with the database into third party software, please contact the authors.

6 Conclusion

To understand and model the behavior of complex fenestration systems, the interest in bidirectional transmission and reflection distribution functions (BTDFs and BRDFs) has grown significantly over the last two decades. Over this period of time, several experimental devices have emerged, called goniopho-

tometers. Unlike integrating spheres that are used to record the directional-hemispherical transmission or reflection of a material, goniophotometers are able to assess spatially resolved light transmission or reflection distributions.

This paper presents a critical review of nine such goniophotometric test facilities, and points out their respective innovations and capabilities. Two radically different assessment approaches were found, one based on a scanning process (7 instruments) and one based on digital imaging combined with a projection principle (2 devices). The advantages and shortcomings of these two methods are discussed: scanning-based approaches are oftentimes easier to reproduce due to less complex calibration procedures while video-based approaches are much more time-efficient and offer a continuous investigation of the light flux distribution.

Recently, physical measurements are being complemented by numerical approaches based on ray-tracing calculations. They require the characterized system to be of well-known properties, which makes these methods more valuable for early design and optimization of products, or for testing out different configurations of a system including fully characterized individual components. If efficiently combined with measurements, expenses related to the construction and maintenance of large experimental facilities can thus be reduced and costs for system-prototyping significantly lowered.

As bidirectional light transmittance through CFS (or bidirectional reflectance on materials) are dependent on four parameters (incident light altitude and azimuth, emerging light altitude and azimuth), and as outside illumination conditions vary greatly over time, indoor light penetration is hard to predict if BT(R)DF values and sky luminance distribution patterns are kept as raw data.

Today's important efforts in BT(R)DF assessment have therefore to be combined with similar efforts in making these data usable for design decisions. New algorithms calculating candle power distributions based on raw BTDF data and outside luminance distributions have therefore been developed to convert these data into usable input for lighting simulation software used in daily practice. These algorithms are combined with a new database management interface, that includes an intuitive graphical user-interface. This integration makes the benefits of choosing one CFS rather than another depending on the sky and room conditions easily identified by the designer (in a way comparable to luminaire selection in artificial lighting programs), and more generally, allows the latter to view, analyze and hopefully optimize the illumination conditions of a room containing one or more Complex Fenestration Systems.

Acknowledgements

This work was realized within the framework of Task 31 of the International Energy Agency (IEA), Solar Heating and Cooling Programme (SHC).

Marilyne Andersen was supported by the Swiss Federal Institute of Technology (EPFL) and the Commission for Technology and Innovation (CTI) during her PhD thesis, as well as by a joint funding from the Lawrence Berkeley National Laboratory and the Swiss National Science Foundation, fellowship 81EL-66225, during her stay at LBNL. She is supported by the Massachusetts Institute of Technology since July 2004. She would like to thank Lambda Research Corporation for having provided her with a license of TracePro® to complete this research.

Jan de Boer was supported by the German Ministry of Economics and Labour (BMWA) under Grant Nb. 0329037G and by the ADELINE User Club. The database has been developed within the framework of a joint project with the Fraunhofer-Institute for Solar Energy Systems, system developers, and consultant offices.

References

[1] Commission Internationale de l'Eclairage. Radiometric and photometric characteristics of materials and their measurement. *CIE*, 38(TC-2.3), 1977.

[2] J.-L. Scartezzini and B. Paule. Office Lighting. Technical report, EDMZ, Bern, 1994.

[3] M. Fontoynont. Properties of glazings for daylighting applications. Final Report JOU2-CT940404, ENTPE, Lyon, France, September 1995.

[4] C.F. Reinhart and S. Herkel. The simulation of annual daylight illuminance distributions a state-of-the-art comparison of six RADIANCE-based methods. *Energy and Buildings*, 32(2):167–187, July 2000.

[5] International Energy Agency. *Daylight in Buildings - A source book on daylighting systems and components.* IEA SHC Task 21 / ECBCS Annex 29, Berkeley, July 2000.

[6] R. Mitanchey, L. Escaffre, and C. Marty. From optical performances characterization of a redirecting daylight material to daylighting simulations. In *Proceedings of the 3rd European Conference on Energy Performance & Indoor Climate in Buildings EPIC 2002*, pages 721–726, Lyon, France, Oct. 23-26, 2002. ENTPE.

[7] J. de Boer. Modelling indoor illumination by complex fenestration systems using bidirectional photometric data. *Energy and Buildings*, In Press.

[8] M. Dirksmöller and H. Erhorn. Adeline 3.0. Documentation, Fraunhofer Institute of Building Physics, Suttgart, 1999.

[9] M. Andersen. *Innovative bidirectional video-goniophotometer for advanced fenestration systems.* PhD thesis, EPFL, Lausanne, 2004.

[10] Illuminating Engineering Society of North America. *Lighting Handbook.* IESNA, New York, 1993.

[11] Commission Internationale de l'Eclairage. The photometry and goniophotometry of luminaires. *CIE*, 121, 1996.

[12] P.R. Tregenza. Subdivision of the sky hemisphere for luminance measurements. *Lighting Research and Technology*, 19(H.1):13–14, 1987.

[13] M. Andersen. Light distribution through advanced fenestration systems. *Building Research and Information*, 30(4):264–281, July 2002.

[14] Commission Internationale de l'Eclairage. The Measurement of Luminous Flux. *CIE*, 84, 1989.

[15] J.F. Murray-Coleman and A.M. Smith. The Automated Measurement of BRDFs and their Application to Luminaire Modeling. *Journal of the Illuminating Engineering Society*, 19(1):87–99, 1990.

[16] S.C. Foo. A gonioreflectometer for measuring the bidirectional reflectance of material for use in illumination computation. Master's thesis, Cornell University, Ithaca, NY, August 1997.

[17] P.A. van Nijnatten. An automated directional reflectance/transmittance analyser for coating analysis. *Thin Solid Films*, 442(1-2):74–79, October 2003.

[18] I. Ashdown and R. Rykowski. Making Near-Field Photometry Practical. *Journal of the Illuminating Engineering Society*, 27(1):67–79, 1998.

[19] R. Rykowski. Illumination System Measurement Using CCD Cameras. In *International Optical Design Conference, Technical Digest*, Washington, DC, 1994. Optical Society of America.

[20] I. Lewin and J. O'Farrell. Luminaire Photometry Using Video Camera. *Journal of the Illuminating Engineering Society*, 28(1):57–63, 1999.

[21] D.R. Jenkins and H. Mönch. Source Imaging Goniometer Method of Light Source Characterization for Accurate Projection System Design. In *2000 Society for Information Display Conference*, Long Beach, CA, 2000. SID.

[22] S. Tsuchida, I. Sato, and S. Okada. Measurement of land surface brdf with spatial instability for vicarious calibration. In *Proceedings of SPIE - The International Society for Optical Engineering Vol. 3870*, pages 254–258, 1999.

[23] A. Demircan, R. Schuster, M. Radke, M. Schnermark, and H.P. Rser. Use of a wide angle CCD line camera for BRDF measurements. *Infrared Physics & Technology*, 41(1):11–19, February 2000.

[24] S.R. Sandmeier. Acquisition of Bidirectional Reflectance Factor Data with Field Goniometers. *Remote Sensing of Environment*, 73:257–269, 2000.

[25] K.F. Karner, H. Mayer, and M. Gervautz. An Image based Measurement System for Anisotropic Reflection. *Computer Graphics Forum*, 15(3):119–

128, September 1996.

[26] S.R. Marschner, S.H. Westin, E.P.F. Lafortune, K.E. Torrance, and D.P. Greenberg. Image-based BRDF measurement including human skin. In *Proceedings Eurographics Workshop on Rendering*, Granada, Spain, June 21-23, 1999.

[27] H.P.A. Lensch, J. Kautz, and M. Goesele. Image-Based Reconstruction of Spatial Appearance and Geometric Detail. *ACM Transactions on Graphics*, 22(2):234–257, April 2003.

[28] K.J. Dana, B. van Ginneken, S.K. Nayar, and J.J. Koenderink. Reflectance and Texture of Real-World Surfaces. *ACM Transactions on Graphics*, 18(1):1–34, January 1999.

[29] J. Breitenbach and J.L.J. Rosenfeld. Design of a Photogoniometer to Measure Angular Dependent Optical Properties. In *Proceedings of International Conference on Renewable Energy Technologies in Cold Climates*, pages 386–391, Ottawa, Canada, 1998. Solar Energy Society of Canada Inc.

[30] P. Apian-Bennewitz, J. von der Hardt, and M. Goller. Characterization of aerogels for computer simulations. November 1994.

[31] K.M. Papamichael, J. Klems, and S. Selkowitz. Determination and Application of Bidirectional Solar-Optical Properties of Fenestration Materials. Technical Report LBL-25124, Lawrence Berkeley National Laboratory, Berkeley, 1988.

[32] J.H. Klems. A new method for predicting the solar heat gain of complex fenestration systems - I: Overview and derivation of the matrix layer calculation. In *ASHRAE Winter Meeting*, New Orleans, LA, Jan. 22-26, 1994.

[33] J.H. Klems and J.L. Warner. Measurement of bidirectional optical properties of complex shading devices. In *ASHRAE Transactions 101 (1)*, pages 791–801, Chicago, IL, 1995.

[34] J.H. Klems, J.L. Warner, and G.O. Kelley. A comparison between calculated and measured SHGC for complex glazing systems. In *ASHRAE Transactions 102 (1)*, pages 931–939, Atlanta, Feb. 17-21 (1996), 1997.

[35] R. McCluney and J. Sung. Simulation of venetian blind optical properties with monte carlo ray tracing. Technical report, Florida Solar Energy Center, Cocoa, FL, December 1999.

[36] P. Apian-Bennewitz. Designing an apparatus for measuring bidirectional reflection/transmission. In *Proceedings SPIE Vol. 2255, Optical Materials Technology for Energy Efficiency and Solar Energy Conversion XIII*, pages 697–706, 1994.

[37] P. Apian-Bennewitz and J. von der Hardt. Enhancing and calibrating a goniophotometer. *Solar Energy Materials and Solar Cells*, 54(1-4):309–322, August 1998.

[38] P. Apian-Bennewitz. *Messung und Modellierung von lichtstreuenden Materialien zur Computer-Simulation von Tageslichtbeleuchtung.* PhD thesis, Albert-Ludwigs-Universität, Freiburg, 1995.

[39] P. Apian-Bennewitz. pab gonio-photometer ii. Internet WWW page at URL: <http://www.pab-opto.de//> (Accessed 01/12/06), 2006.

[40] G.B. Smith. Photogoniometer at the university of technology, sydney. International Daylighting RD&A, 2-99 (8), p. 13, September 1999. University of Sydney, Australia.

[41] G.B. Smith, D.C. Green, G. McCredie, M. Hossain, P.D. Swift, and M.B. Luther. Optical characterisation of materials and systems for daylighting. *Renewable Energy*, 22(1-3):85–90, January-March 2001.

[42] S. Aydinli. Short description of the spiral goniophotometer for bi-directional measurements (TU Berlin). Report for IEA SHC Task 21, ECBCS Annex 29, Subtask A, Technische Universität Berlin (TUB), Berlin, 1996.

[43] L. Bakker and D. van Dijk. Measuring and processing optical transmission distribution functions of TI-materials. Private Communication, TNO Building and Construction Research, Delft, 1995.

[44] D. van Dijk. Daylighting Products with Redirecting Visual Properties (The project REVIS). Final Report JOE3-CT98-0096, TNO Building and Construction Research, Delft, February 2001.

[45] J.L.J. Rosenfeld. On the calculation of the total solar energy transmittance of complex glazings. In *Proceedings of the 8th International Meeting on Transparent Insulation*, Freiburg, Germany, 1996.

[46] J. Breitenbach, S. Lart, I. Längle, and J.L.J. Rosenfeld. Optical and thermal performance of glazing with integral venetian blinds. *Energy and Buildings*, 33(5):433–442, May 2001.

[47] I. Lewin, R. Laird, and J. Young. Video photometry for quality control - CCD technology produces an all-terrain photometer system. LD&A, pp. 16-20, January 1992.

[48] K.D. Song, L.O. Degelman, and L.L. Boyer. Determining Daylighting Parameters by a Luminance Mapping System and Scale Models. *Journal of the Illuminating Engineering Society*, 23(1):65–75, 1994.

[49] V. Berrutto and M. Fontoynont. Applications of CCD cameras to lighting research: Review and extension to the measurement of glare indices. In *Proceedings CIE 119, 23rd Session*, pages 192–195, New Delhi, 1995.

[50] C. Loscos. *Ré-éclairage et Remodélisation Interactifs des Scènes Réelles pour la Réalité augmentée*. PhD thesis, Université Grenoble I, Grenoble, December 1999.

[51] L. Michel and M. Andersen. Réalisation d'un photo-uranotomographe à imagerie numérique. In *Proceedings Solar Energy in Buildings CISBAT'99*, pages 289–294, Lausanne, Sept. 22-23, 1999. EPFL.

[52] D. Francioli and J.-J. Meyer. Etude de l'éblouissement au moyen d'un photoluminancemètre numérique. In *Proceedings CISBAT 2003*, pages 265–270, Lausanne, Oct. 8-9, 2003. EPFL.

[53] G.J. Ward. Measuring and modeling anisotropic reflection. *ACM SIGGRAPH Computer Graphics*, 26(2):265–272, July 1992.

[54] J.-M. Deniel. *Modélisation des luminaires et des BRDF: réalisation,*

mesure et compression. PhD thesis, Université de Rennes 1, Rennes, April 2002.

[55] M. Andersen, D. Ljubicic, C. Browne, S. Kleindienst, and M. Culpepper. Combining time-efficient goniophotometry with scale model studies in a unique instrument. In *Proceedings of Lux Europa 2005 - Lighting for Humans*, pages 271–274, Berlin, September 19-21, 2005. Deutsche Lichttechnische Gesellschaft e.V. (LiTG).

[56] M. Andersen, L. Michel, C. Roecker, and J.-L. Scartezzini. Experimental assessment of bi-directional transmission distribution functions using digital imaging techniques. *Energy and Buildings*, 33(5):417–431, May 2001.

[57] M. Andersen, C. Roecker, and J.-L. Scartezzini. Design of a time-efficient video-goniophotometer combining bidirectional functions assessment in transmission and reflection. *Solar Energy Materials and Solar Cells*, 88(1):97–118, June 2005.

[58] M. Andersen. Validation of the performance of a new bidirectional video-goniophotometer. *Lighting Research and Technology*, In Press.

[59] M. Andersen, M. Rubin, and J.-L. Scartezzini. Comparison between ray-tracing simulations and bi-directional transmission measurements on prismatic glazing. *Solar Energy*, 74(2):157–173, February 2003.

[60] M. Andersen, M. Rubin, R. Powles, and J.-L. Scartezzini. Bi-directional transmission properties of venetian blinds: Experimental assessment compared to ray-tracing calculations. *Solar Energy*, 78(2):187–198, 2005.

[61] M. Moeck. On daylight quality and quantity and its application to advanced daylight systems. *Journal of the Illuminating Engineering Society*, 27(1):3–21, 1998.

[62] N.S. Campbell. *A Monte Carlo approach to thermal radiation distribution in the built environment*. PhD thesis, University of Nottingham, Nottingham, January 1998.

[63] R. Compagnon. *Simulations numériques de systèmes d'éclairage naturel à pénétration latérale*. PhD thesis, Ecole Polytechnique Fédérale de Lausanne, Lausanne, 1994.

[64] T.E. Kuhn, C. Bühler, and W.J. Platzer. Evaluation of overheating protection with sun-shading systems. *Solar Energy*, 69(Suppl. 6):59–74, July-December 2001.

[65] W.J. Platzer. Basic data for model calculations of solar shading systems. Report for IEA SHC Task 27, Subtask A T27-A3-FRG-WJP-2001-2, Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany, January 2002.

[66] C.F. Reinhart and O. Walkenhorst. Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. *Energy and Buildings*, 33(7):683–697, September 2001.

[67] R. Mitanchey, G. Periole, and M. Fontoynont. Goniophotometric measurements: Numerical simulation for research and development applications. *Lighting Research and Technology*, 27(4):189–196, 1995.

[68] Opticad. Optical Analysis Program User's Guide Version 7.0. Opticad Corporation, 2001. Santa Fe.

[69] J. de Boer. Numerical goniophotometer. User Manual, Fraunhofer Institute of Building Physics, Stuttgart, 2004.

[70] J. de Boer. *Tageslichtbeleuchtung und Kunstlichteinsatz in Verwaltungsbauten mit unterschiedlichen Fassaden.* PhD thesis, Universität Stuttgart, Stuttgart, 2004.

[71] S. Wössner and J. de Boer. Plugin-technologies for daylight design tool applications. Working Document of IEA SHC TASK 31 (Daylighting Buildings in the 21st century) T27-A3-FRG-WJP-2001-2, Fraunhofer Institute of Building Physics, Suttgart, Germany, 2004.

List of Tables

Institute	BTDF	BRDF	Coverage	Direc	λ_{dep}	Time	Validation	Replica
LBNL, USA	✓	-	discrete	sample	-	∼4 days	g-val. comp. (10%)	☺
ISE, Germany	✓	✓	discrete	BTF	-	∼4 days	old: $\int_{sphere}$ (5%-61%); new: under devlpmt	☹
pab®-opto, Germany	✓	✓	discrete	sample	✓	∼4 days	not published	☺
TUB, Germany	✓	-	discrete	sample	-	∼4 days	under devlpmt	☹
TNO, The Netherlands	✓	✓	discrete	not publ.	-	∼4 days	$\int_{sphere}$ (10%-20%)	☹
DTU, Denmark	✓	-	discrete	±0.5°	✓	∼30 days	$\int_{sphere}$, g-val., an. model (∼11%)	☹
UTS, Australia	✓	✓	discrete	sample	-	∼4 days	not published	☹
EPFL, Switzerland	✓	✓	full	sample	-	8 hours	$\int_{sphere}$, an.model, ray-trac., BTDF comp. (2%-14%)	☹
MIT, USA	✓	✓	full	sample	✓	< 10 min	under devlpmt	☹

Table 1
Main features of current bidirectional goniophotometer designs for the experimental assessment of façade components and fenestration systems.

Type of system	Name of product	Symmetry	Nb inc. dir.	Institute
Diffusing materials	Opal. plexiglas	1	14	LESO/EPFL
”	”	”	7	TUB
”	Opal. plastic	1	3	LESO/EPFL
”	”	”	3	TNO
”	Diffusing paint	1	1	LESO/EPFL
Sunlight redirect. syst.	Laser Cut Panel	4	56	LESO/EPFL
”	Acrylic stripes	4	18	LESO/EPFL
”	Lumitop^{TM}	3	76	LESO/EPFL
”	”	”	61	TUB
”	Serraglaze^{TM}	3	76	LESO/EPFL
”	Holographic film	3	35	LESO/EPFL
”	Curved squ. mirrors	4	17	LESO/EPFL
”	Curved asym. mirrors	3	20	LESO/EPFL
Prismatic panels	Siemens 45° prism	4	48	LESO/EPFL
”	Siemens 42°/5° prism	3	35	LESO/EPFL
”	3M SOLF^{TM} film	4	113	LESO/EPFL
”	”	”	33(poor)	ISE
Fabric blinds	19 B.-H.* blinds	1 or 4	5 x 19	LESO/EPFL
”	4 REVIS samples	1 or 4	3 x 4	LESO/EPFL
”	4 REVIS samples	”	3 x 4	TNO
Venetian blinds	OKASolar^{TM}	3	18	LESO/EPFL
”	OKASolar^{TM} “S”	3	76	LESO/EPFL
”	9 B.-H.* mirror blinds	3	23 x 9 x 3**	LESO/EPFL
”	3 Köster blinds	3	23 x 3 x 3**	LESO/EPFL
”	4 B.-H.* painted blinds	3	7 x 4	LESO/EPFL

Table 2
Overview of the measured BT(R)DF datasets generated at LESO-PB/EPFL, TNO, TUB and ISE (physical goniophotometers): *B.-H. stands for Baumann-Hüppe AG; **x 3 relates to the 3 slats configurations that were considered for each blind: 0°, 45° and 90°).

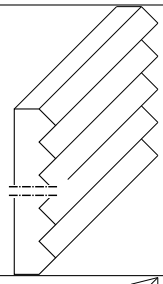
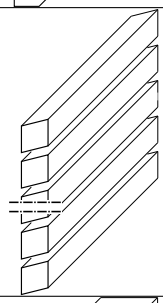
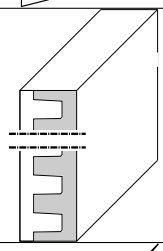
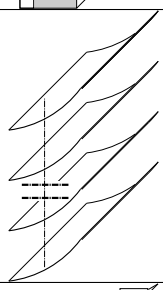
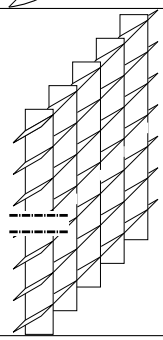
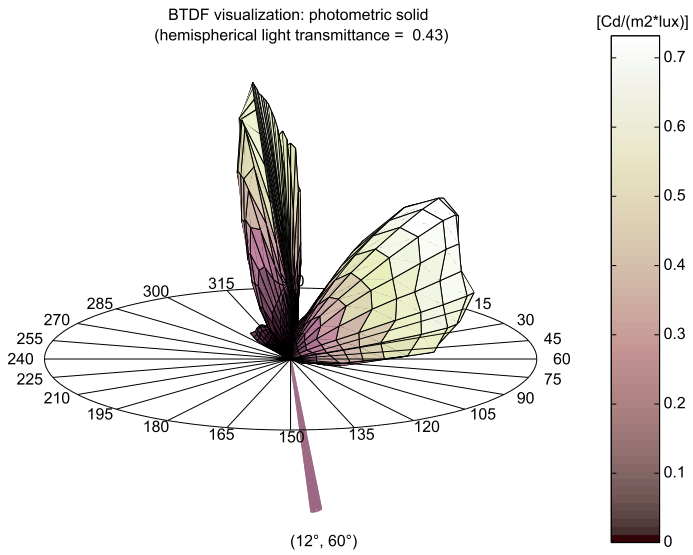
System	Figure	Key Parameters
Prism		• index of refraction • thickness • angle of prism elements
Laser Cut Panel		• index of refraction • thickness of panel • distance of cuts • angle of cuts
Light Redirecting Glass		Ready to buy light guiding system based on same optical principle as Laser Cut Panel. Can be parametrized for test purposes.
Blinds		• specular and diffuse reflection • slat curvature: cylindrical or parabolic • distance and number of slats • slats incline
Gratings		• specular and diffuse reflection • distance of grating slats • incline of grating slats

Table 3
Selection of CFS-models currently supported by the CFS-Sample Generator with key configuration parameters.

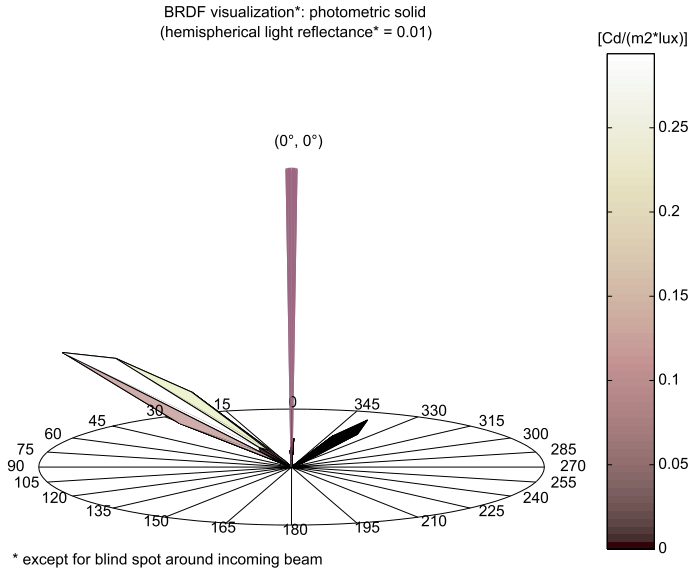
Type of system	Name of product	Symmetry	Nb inc. dir.	Institute
Hole	BTDF of a hole. For testing purposes	1	76	FHG/IBP
Diffusor	BTDF of an ideal diffusor. For testing purposes	1	76	FHG/IBP
Sunlight redirect. syst.	45° Prism	4	76	FHG/IBP
”	”	”	8	LESO/EPFL
”	42°/5° Prism	3	20	LESO/EPFL
”	Laser Cut Panels	4	76	FHG/IBP
”	”	”	76	LESO/EPFL
”	Serraglaze^{TM}	3	76	FHG/IBP
”	”	”	76	LESO/EPFL
Venetian blinds	diffusing blinds	3	76 x 10*	FHG/IBP
”	mirror blinds	3	76 x 20*	FHG/IBP
”	B.-H. mirror blinds	3	15**	LESO/EPFL

Table 4
Overview of the computed BTDF datasets generated at LESO-PB/EPFL and FHG-IBP (numerical goniophotometers): * according to the manufacturer's specifications, calculated for different slat inclinations from *system open* to *system closed*; ** calculated for 15 incident directions at slat tilts 0°and 45°.

List of Figures



(a) BTDF, incidence (12°, 60°)



(b) BRDF, incidence (0°, 0°)

Fig. 1. BTDF and BRDF representations as photometric solids for the sun-directing glass "Lumitop^{TM}" and a Holographic Optical Element (source: [9]).

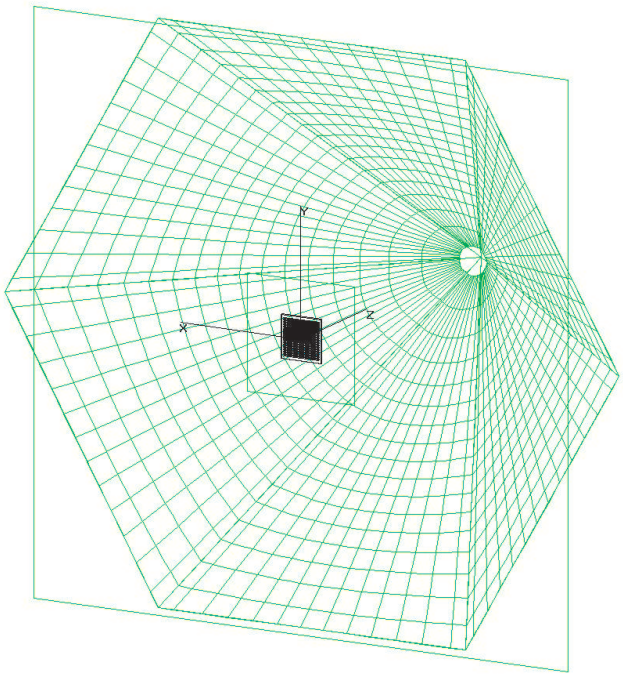


Fig. 2. Simulation model composed of an opaque diaphragm, the analyzed sample, a non-interacting incident flux detection surface and six absorbing detection screens split into adjacent angular sectors.

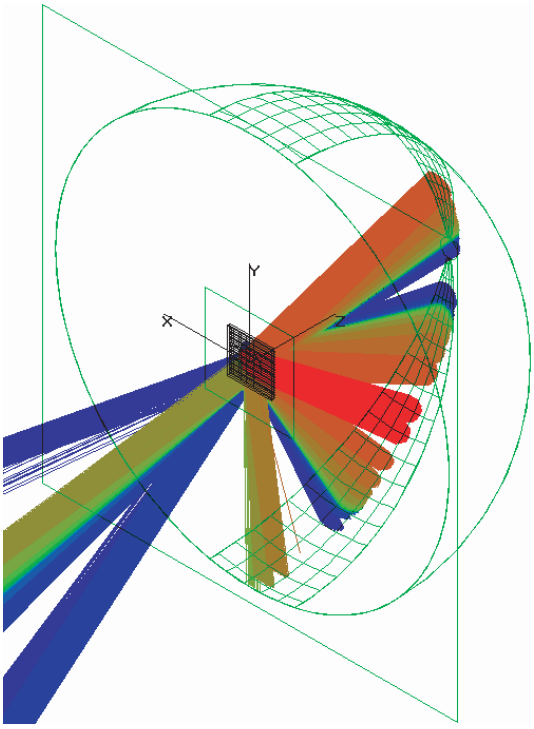
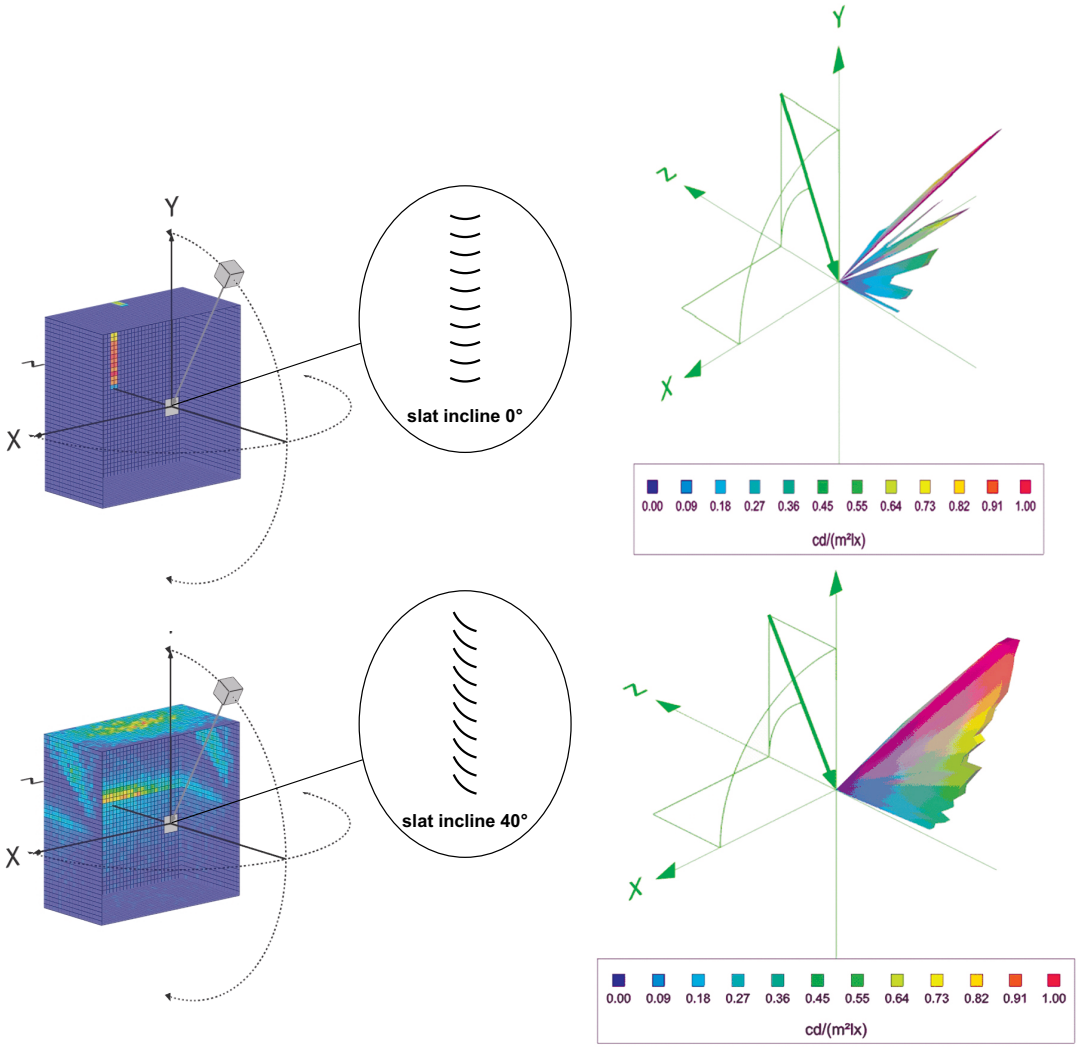


Fig. 3. Ideal set-up model configuration: hemispherical absorbing detector and virtual sun.



(a) Fluxdetection on hemicube

(b) Normalized BTDF at slat inclination 0° (upper figure: 10,000 traced rays, lower figure 1,000,000 traced rays.

Fig. 4. Illustration of FHG-IBP numerical goniophotometer. The flux detected on the sensor planes of the hemicube is converted into luminance coefficients (BTDF values).

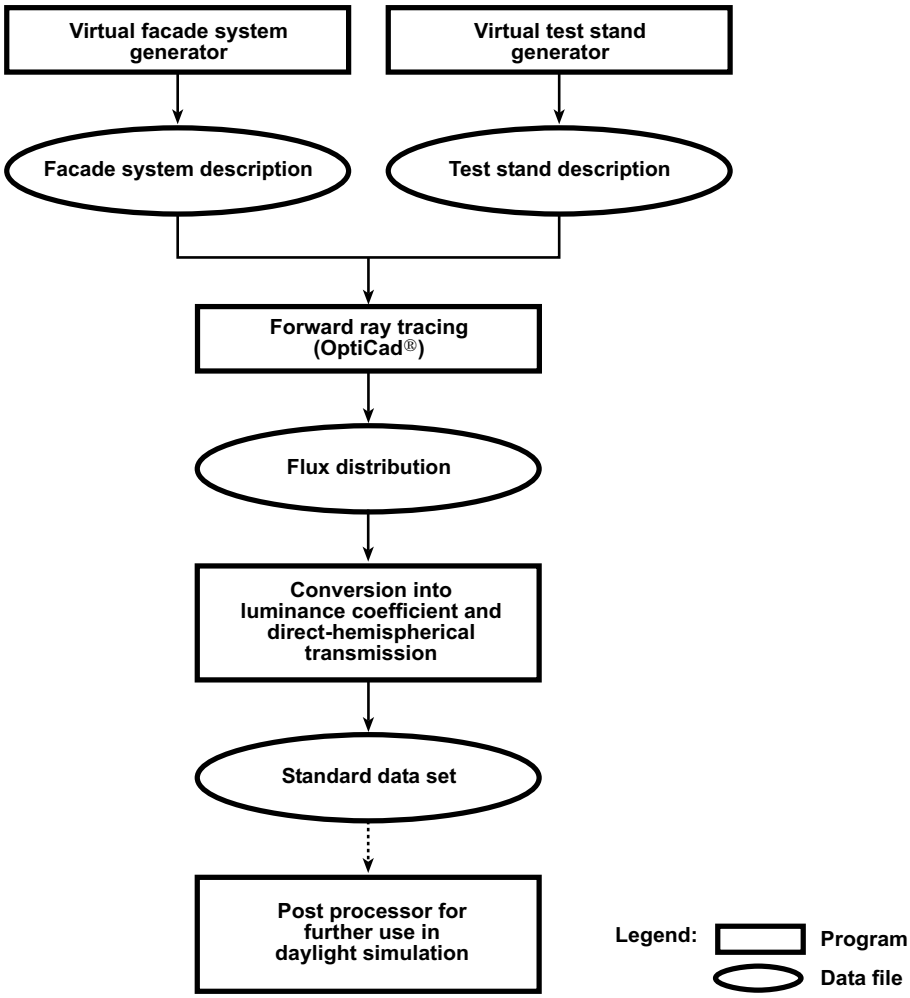


Fig. 5. Flowchart illustrating the program interaction and dataflow of the FHG-IBP numerical goniophotometer environment.

Fig. 6. Photo-realistic visualization of room illuminated by standard venetian blinds in the lower façade area and a light redirecting glass in the upper façade area.