Experimental and simulation-based approaches to assess bidirectional properties of complex fenestration systems

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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 optimize their products and architects in selecting the latter judiciously already at the project's level. It will also help daylighting simulation tool designers to improve their programs' performances and achieve a reliable modeling 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 almost all based on a scanning process /2,3,4,5,6,7,8,9/ i.e. on relative individual movements of the detector and of the sample and/or the source to monitor all incoming and outgoing light flux directions for which BT(R)DF data are needed, except for one /10,11/ and another under development /12/ both relying on a flux-based investigation combining the use of digital imaging for detection with the collection of the light emerging from the sample on a projection surface (diffusing screen for /10,11/ or mirrored ellipsoid for /12/).

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 one 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.

The angular-dependent light transmittance through complex fenestration systems (CFS) and the interaction with outside illuminance conditions provides spatial and time variant indoor light penetration of generally much higher complexity compared to standard glazing systems. These dependencies have to be made transparent to the designer in an easy to handle way, such that for specific problems the best solution can be found at low expenses. Therefore a database with a flexible user-interface is being introduced in the third part of the paper. This software aims at comparable software support for CFS as for luminaire selection in artificial lighting design. Amongst other features, it allows to view the different data sets in a graphically interactive way. As a function of façade orientation and tilt, the daylight distribution into indoor spaces can be displayed and analyzed. Whenever available, the database system will provide additional information like figures, pictures, and text.

2. Review of existing experimental goniophotometric devices for façade components

Chart 1 summarizes the main features of the different instruments developed for advanced fenestration systems by providing the corresponding research institute, the specific detection device, the type of monitored measurements, the sample size and publishing year of related literature references.

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Institute	Sensor	BTDF	BRDF	Sample (cm^2)	Date
LBNL, USA	silicon photodiode	✓	-	40×40	1988/94/95/97
ISE, Germany	silicon photodiode	✓	✓	$\leq 40 \times 40$	1994/98
TNO, The Netherlands	silicon photodiode	✓	✓	$\leq 80 \times 80$ (only $\simeq 1$ cm observed)	1995/2001
TUB, Germany	photoelement	✓	-	$\in [5\times 5\,;15\times 15]$	1996/98
ILB, Germany	spectrometer	✓	✓	$\leq 7.5 \times 7.5$	1996/98
Cardiff, United Kingdom	optical fiber + silicon / InGaAs	✓	-	$\leq 9 \times 9$	1996/98 2000/01
UTS, Australia	radiometer	✓	✓	$\leq 40 \times 40$	1999/2001
LESO, Switzerland	CCD camera	✓	✓	$\leq 40 \times 40$	1999 2000/01/02/03/04
Pab®-opto, Germany	multiple (IR,visible,multichannel)	✓	✓	$\leq 30 \times 30$	under devlpmt
MIT, USA	CCD camera	✓	✓	$\leq 15 \times 15$	under devlpmt

Char. 1. Main features of existing bidirectional goniophotometers for the experimental assessment of façade components and fenestration systems.

2.1 Pros and cons of a scanning-based assessment

The two main draw-backs of the scanning approach are the considerable measurement time needed for a BT(R)DF assessment, which is further increased when another angular resolution is required due to rapidly varying luminances, and more importantly the fact that the investigation is discrete. A preliminary scanning is often required to locate the luminous “peaks” while the risk of missing some significant feature can never be avoided completely. Irregular resolutions also make it more difficult for simulation programs to implement the BT(R)DF data and the estimation of the global (directional-hemispherical) transmittance or reflectance becomes delicate as a weighting of data is then necessary, based on the areas associated to each point /13/. On the other hand, when using specific detection techniques, an optimal accuracy can be achieved with this approach when assessing the light distribution's directionality. Indeed, focusing the emitted light rays onto a detector showing an opening angle as close as possible to their accepted divergence (typically ±0.5°), a very accurate spatial characterization can be ensured, as for the Cardiff goniospectrometer /3/, its technique having recently been adopted at TNO as well /5/.

When the measured luminance and the emerging direction are on the other hand average values obtained over the whole sample area, as for the device developed at LBNL e.g. /2/, the detection surface must be able to encompass the possible divergence of the rays that reach it, either choosing a sensor element of appropriate dimensions, or compensating a too small or too close detector by averaging data obtained at different positions within the target space portion.

2.2 Pros and cons of a flux-based assessment

The idea is here to collect the light emerging from the sample on a projection surface, at which a calibrated digital camera is pointed, used as a multiple-points luminance-meter. In /10,11/, this surface is a diffusing triangular panel thus six positions of the screen and camera around the sample (each separated by a 60° rotation from the next one) are needed to get a complete and continuous investigation of the transmitted or reflected light, which is achieved within a few minutes per incident direction. This very time-efficient approach for bidirectional measurements allowed an extensive database of BTDF and BRDF to be generated, including diffusing materials, sunlight redirecting systems (such as laser cut panels, holographic films, etc.), prismatic panels and fabric and venetian blinds of many kinds. Today, this is by far the largest available BT(R)DF database available (it is described in the Appendix C of ref /14/. In /12/, the detection principle imagined by Ward /15/ for photo-realistic rendering of lighting in interior spaces was adopted: the sample and a CCD camera equipped with a fish-eye lens are each positioned at the two focal points of a hemi-ellipsoidal, semi-transparent mirror. The investigation of the whole emerging light distribution is therefore achieved within basically a unique image capture for each incident direction.

Choosing to point an imaging detector towards a projection surface to assess BT(R)DFs allows to combine time-efficiency with continuity of information, as a single digital image gathers thousands of emerging directions without any gap between them. 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 limitation.

From the luminance mappings offered by the once calibrated digital images, the light flux distribution can be subdivided according to an angular grid of freely chosen intervals in altitude and azimuth, defining contiguous sectors where the BT(R)DF can be averaged without any loss of precision as each mean value will truly represent the angular interval it is associated to, and will not correspond to an infinitesimal solid angle around a given emerging direction. Such BT(R)DF data will then be different from goniophotometric measurements based on a scanning process, unless the investigated material presents perfectly diffusing properties (or unless the averaging sectors become of size comparable to the divergence of detected rays for a given position of the scanning sensor).

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.

However, as there are many procedures necessary to extract the desired output from raw digital images, these advantages are only accessible at the expense of numerous calibration procedures as well as heavy image and data processing /14/, and the reliability of the data assessment and its related accuracy depend on their careful execution. Of course, once all the intermediate conversions have been implemented successfully, the measurement facility becomes again as easy to use as any instrument of the kind.

On the other hand, such an assessment method prevents from being able to achieve a spatial accuracy as optimal as for the instrument developed at Cardiff University /3/, as the measured luminances and emerging directions are average values for the sampled region. As mentioned before, it is therefore important to subdivide the emerging hemisphere according to an averaging grid in agreement with the possible divergence of rays reaching a given point on the screen.

3. Assessment of bidirectional distribution functions using numeric methods

Ray-tracing simulations provide a useful tool for evaluating complex systems in full detail. Many assessment methods for the optical performances of glazing or shading systems 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 /16/;
- to test a new ray-tracing approach for thermal radiation /17/ or prismatic panel performances /18/;

- 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® /19,20/;
- to determine the daylight distribution in a room and compare Radiance simulations with office room monitoring /21/.

Based on these methods, three virtual goniophotometers have been realized, that are described below. All of them adopted a flux-based method, splitting the detection surface into adjacent angular sectors, as mentioned for the video-based experimental approaches of Section 2.2.

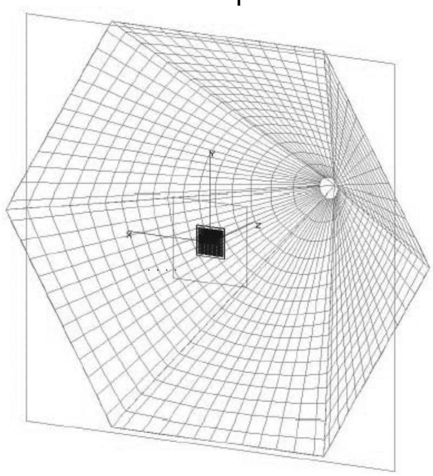
3.1 LESO-PB/EPFL virtual goniophotometer using TracePro®

The experimental conditions described in Section 2.2 for the LESO-PB/EPFL instrument referenced in /10,11/ were reproduced virtually /22,23/ with the commercial forward ray-tracer TracePro® (Lambda Research Corporation, Inc.) that is based on Monte Carlo calculations. Computer simulation results were then compared to BTDF data assessed with the experimental goniophotometer.

Both the light source and detection device were simulated with characteristics as close as possible to the reality, although by essence, the model will not take the inevitable imperfections proper to any physical component into account. These differences are therefore to be included in the model error estimation.

The major constraints for the simulation model are:
- the virtual light source must be of same angular spread as the real one: a set of wavelengths representative of its spectrum were determined and the source positioned in order to reproduce the same incident directions as for the experimental assessment of BTDFs;
- the model of the sample must present identical geometrical and physical properties, and the area exposed to light must fit the experimental illuminated surface;
- a detection screen model of same geometry as the one used for the measurement facility is needed, separated into the same pattern of “averaging” sectors.

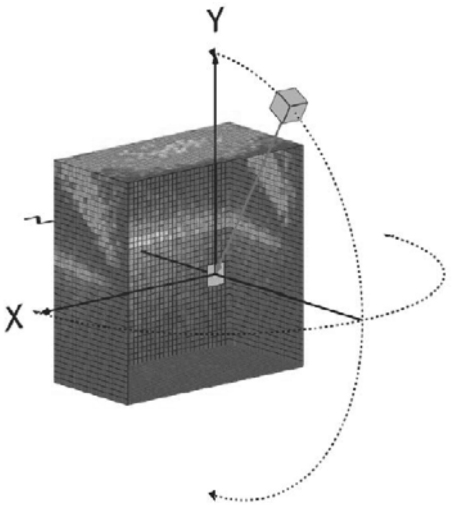
More details about this virtual goniophotometer, illustrated in Picture 1, and about the chosen simulation parameters can be found in /22,23/.



Pict.1. Simulation model of the LESO-PB/EPFL goniophotometer.

3.2 FHG-IBP Numerical Goniophotometer Environment using OptiCad®

The FHG-IBP numerical goniophotometer has been developed as an alternative method of including CFS into the process of daylight design and simulation /24,25/. It is illustrated in Picture 2 and represents an automated environment allowing to configure the virtual test set up, parameterize and combine CFS samples and postprocess data for further use in daylight simulation. The environment is based on the commercial forward ray-tracing tool OptiCad® /26/ and generally follows the flux based method described earlier. The procedure has been validated against analytical and measured reference cases.



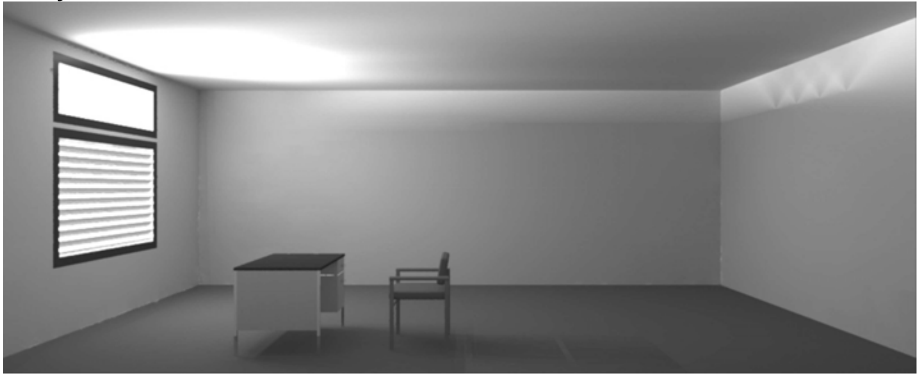
Pict. 2. Illustration of FHG-IBP numerical goniophotometer. The flux detected on the sensor planes of the hemicube is converted into luminance coefficients (BTDF values).

3.2.1 Virtual Test-stand

The virtual test-stand does not directly model a specific existing goniophotometer. As depicted in Picture 2, sensor planes that record the flux coming from the sample are arranged as a hemicube. The virtual test-stand can be operated to either determine BTDF or BRTF datasets. The set-up parameters can be user-defined. This allows to influence the angular resolution of the B(R)TDF datasets. In addition to this, the accuracy due to near field photometric aspects can be controlled.

3.2.2 CFS-Sample Generator

The software allows to automatically generate different CFS samples without having to directly provide OptiCad® code. Different combinations of CFS components can be arranged in layer structures.



Pict. 3. Photorealistic visualization of room illuminated by standard venetian blinds in the lower facade area and a light redirecting glass in the upper facade area.

3.2.3 Postprocessing

In /27/, a method is offered to calculate the systems' candle power distributions from the outside luminance distribution and the systems' BTDF; these distributions can then be integrated into radiosity or ray-tracing based lighting calculation engines. Picture 3 shows a photo-realistic visualization of a daylit room using a light redirecting glass in the upper area of the façade. Integration into the lighting calculation engines allows the calculation of illuminance conditions due to complex facade systems on arbitrary work surfaces. To use BTDFs in daylighting simulation softwares, data postprocessing is therefore necessary. The data have to be filtered and ought to be compressed in data volume. The Numerical Goniophotometer Environment provides an interface to a postprocessor contained in the set of programs described in /27/.

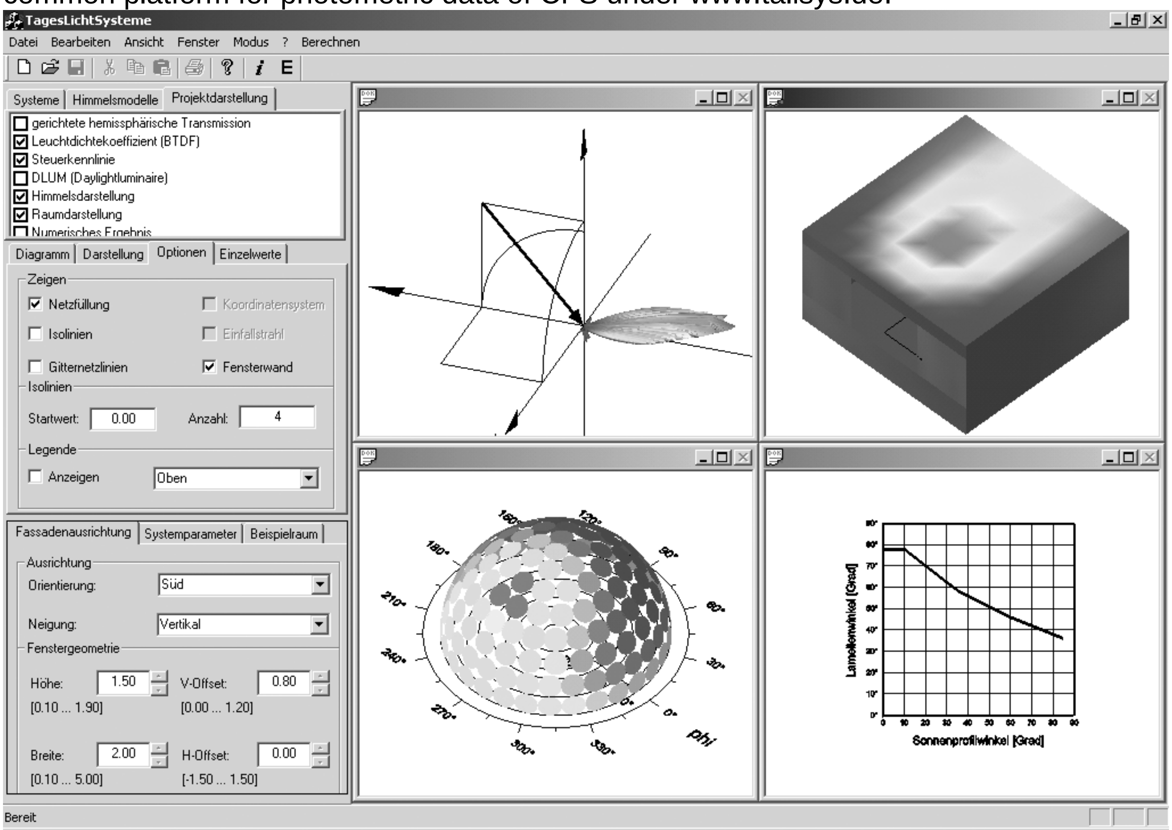
To control the interaction of the different parameters, files and programs, a Graphical User Interface is provided.

3.3 ENTPE simulation methode using Genelux

The Genelux lighting simulation software has been extended to calculate the bidirectional photometric characteristics of samples which can be defined using the available Genelux geometry and material modeling capabilities /28/. Internally, a parallel beam of light is illuminating a sample. One detection hemisphere on the incident side is used to record the BRDF data, a second detection hemisphere on the emitting side records the BTDF data. The obtained values were compared to theoretical solutions for samples such as a lambertian diffusor and glazing panes. For different kinds of venetian blinds with planar slats, cut-off angles have been determined and direct hemispherical transmissions recorded. In order to obtain generalized models of the recorded values, a data fitting was attempted that included specularity peak identification, coordinate transformation wherever necessary, and finally nonlinear data fitting of peaks.

4. Database of CFS bidirectional measurements

The bidirectional light transmittance through CFS and the dependency on outside illuminance conditions delivers spatial and time variant indoor light penetration of generally much higher complexity compared to standard glazing systems. These dependencies have to be made transparent to the designer in an easy to handle way, such that for specific problems the best solution can be identified at low expenses. Therefore a database with a graphical user-interface has been developed aiming at software support for CFS selection comparable to luminaire selection in artificial lighting programs. The database system, illustrated in Picture 4, works on the raw data sets of the CFS. Content viewers allow to visualize the system's functionalities. Benefits of choosing one CFS compared to another under a variety of boundary conditions can be easily identified. This database is offered as a common platform for photometric data of CFS under www.talisys.de.



Pict. 4. Screenshot of the Database.

5. Conclusion

In order to understand and model the behavior of complex fenestration systems, the interest in bidirectional transmission and reflection distributions functions (BTDFs and BRDFs) has grown significantly in building science over the last two decades. Over this period of time, several experimental test devices have emerged. While integrating spheres are normally used for recording the directional-hemispherical transmission or reflection, goniophotometers allow to assess spatially resolved light transmission or reflection. The paper presents an overview of more than 10 such goniophotometric test facilities.

The two different approaches used, a scanning based process and the flux-based process are presented. Scanning based approaches may provide higher angular resolutions, while flux based approaches indicate energetically more robust measurements and generally allow for faster data recording.

Lately the physical measurements have been complemented by numerical ray-tracing based approaches, which all rely on flux-based approaches. These methods require the characterized system to be of well-known properties, that can be modeled with sufficient accuracy both in geometry and coating or material. For these cases the methods promise to be a valuable tool for system design and optimization. Expenses for the construction and maintenance of experimental test facilities can be avoided or reduced. In addition to this, costs for system-prototyping can be significantly lowered.

Important measurement efforts have generated a vast number of BTDF datasets. Over 25 experimentally and 8 numerically recorded datasets of systems are listed. Nevertheless, the use of these datasets in support of daily design decisions still appears to be moderate. The reasons are obvious: the raw data sets are of high complexity and do not directly relate to the later room illumination under specific boundary conditions (e.g. sky luminance distribution, general façade parameters). Also, a lack of simple methods and criteria for inter-comparison of CFS can be identified. On the other hand, a diffusion of the datasets over different institutions, with only a few datasets publicly available, significantly more extensive for one institute (LESO-PB/EPFL), might be an obstacle. The presented database, with an intuitive graphical user-interface, is seeking to overcome some of these deficits.

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