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TOWARDS STANDARDIZED GENERATION OF BSDF DATA DESCRIBING COMPLEX FENESTRATION SYSTEMS

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Summary

Well-informed design decisions are required to tap the full potential of daylight in buildings to improve occupant's health, well-being, and satisfaction, as well as to reduce energy consumption for artificial lighting and cooling. These are hindered by the current lack of standardized methods for modelling advanced daylighting and solar shading systems, which are characterized by their irregular light scattering properties. Transmission through and reflection off such optically complex fenestration systems are described for each pair of incident and outgoing, scattering direction by the Bidirectional Scattering Distribution Function (BSDF). While tabular BSDF data have been called for in ISO/CIE 10916:2024, the lack of a corresponding standard for the generation of such data is problematic. This finding contributed to the ongoing development of ISO/CIE DIS 25176, which formulates a workflow from data-collection through validation to data provision. The future standard should foster the availability of reliable and comparable BSDF data.

Keywords: Bidirectional Scattering Distribution Function BSDF, gonio-photometry, standardization, daylighting, solar shading

Field of application for the findings: Provision of BSDFs for building performance simulation

Addressed audience: Testing laboratories, building scientists, engineers

1. Introduction and Background

Good daylighting in buildings is essential for occupants' well-being and health, as daylight regulates the circadian rhythm, promotes concentration and reduces the risk of health problems such as eye strain or sleep disorders (Knoop et al., 2020). Daylight and view connectivity are central factors for occupant satisfaction (Jamrozik et al., 2019; Lee et al., 2022). At the same time, the optimal use of daylight contributes to energy efficiency by reducing the need for electric lighting and the proper management of solar gains enables minimization of cooling and heating demands. This helps to support sustainable buildings, which offers both ecological and economic benefits (Bashir et al., 2024; IEA SHC Task 61, 2019).

To make full use of these potential benefits is challenging, since continuously changing daylight conditions must be taken into account at all scales of building design, e.g., in early decisions on massing, the layout of floor plans, and the design of building envelopes. Building standards stipulate when and how designers and architects must follow standardized methods and regulations to meet requirements for daylight supply and shading. While these standards often assume standard conditions, e.g., normal incidence under idealized conditions, more advanced methods to characterize angle-dependent, solar-optical properties (transmittance, absorptance, reflectance) are well established for transparent glazing. Such advanced, standardized methods do not exist for so-called complex fenestration systems (CFS), i.e., light scattering, shading and daylighting systems. Methods for characterizing CFSs, referred to in European (EN 14500/14501) and international

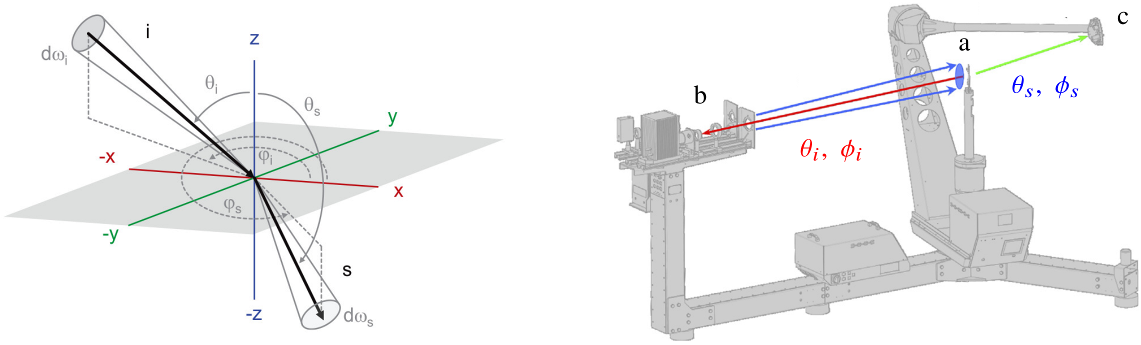

Fig. 1: Left: The BSDF is a general formulation for reflection and transmission as light transport between fractional solid angles $d\omega_i$ and $d\omega_s$, i.e., as a function of incident and outgoing directions θ_i, ϕ_i and θ_s, ϕ_s. Right: Scanning gonio-photometer (Grobe, 2018) acquiring the speciment's average BSDF over the sampling aperture (a) by varying incident and scattered directions to light source (b) and detector (c), respectively (based on illustration by P. Apian-Bennewitz).

standards (ISO52022-1/3:2017-06), are simplified in that they are based on selected normal or hemispherical transmittance and reflectance measurements. This can cause significant errors in the assessment of daylighting and indoor environmental quality, e.g., visual comfort (Wang et al., 2023), as well as for solar gains-related impacts on building energy demand. This in turn renders the objective evaluation of the impact on energy demand, solar distribution, daylight supply, visual comfort, and other aspects of building performance almost impossible. In a comprehensive summary, De Michele et al. (2018) describe why simplified normative methods are often no longer sufficient for building performance simulations and why so-called Bidirectional Scattering Distribution Functions (BSDF) are now frequently used for optical modelling.

BSDFs describe the scattering properties of a surface (Stover, 2025) as a function of incident (source) and scattered (outgoing) directions $\vec{i}$, $\vec{s}$. The latter are notated as off-normal and in-plane angles (θ_i, ϕ_i) and (θ_s, ϕ_s) in this text, as illustrated by Fig. 1, left. Their implicit definition by the 'rendering equation' (Kajiya, 1986) relates the luminance L_s on a scattering object to its BSDF and the integral of the effective light sources' luminances L_i, weighted by their projected solid angle:

$$L_s(\theta_i, \phi_i, \theta_s, \phi_s) = \int^{\omega_i=4\pi} BSDF(\theta_i, \phi_i, \theta_s, \phi_s) \cdot L_i(\theta_i, \phi_i) \cdot |\cos(\theta_i)| \cdot d\omega_i \tag{1}$$

Gonio-photometers measure the BSDF by recording the luminance of a sample by a known light source for variable incident and scattered directions. Since the BSDF is a continuous function, its measurement requires sampling, i.e., the measurement for a discrete set of incident and scattered directions, that constrains the directional resolution of the resulting BSDF data. To acquire the distribution of scattered light and its integral flux, the measurement resolution must sufficiently sample the narrowest features in the distribution of scattered light, which is a convolution of the employed light source and the - yet unknown - BSDF of the specimen. Fig. 1, right illustrates a scanning gonio-photometer [1] (Apian-Bennewitz, 2025), that samples incident and scattered directions by mechanical rotation of sample and detector. The sequential measurement achieves a high dynamic range, allowing to measure both intense specular scattering and weak stray-light, and provides high configurability, e.g., the adaptive refinement of the sampling. An approach to sample at many outgoing directions in parallel is implemented by imaging gonio-photometers. This approach promises the rapid acquisition of BSDFs, but is typically constrained to preset directional resolutions and a limited dynamic range. Initiated by IEA SHC Task 61 / EBC Annex 77, Apian-Bennewitz et al. (2021) recently demonstrated the reliable generation of BSDFs of diffusing and specular shading systems in an international inter-laboratory comparison.

BSDFs have found their way into numerous daylight simulation tools. They are particularly applicable to describe irregular scattering by CFSs (cf. Fig. 2), that can often not be modelled by generic transmission and reflection models. Further, the newly revised version of the standard ISO/CIE 10916:2024 that describes methods for the calculation of the impact of daylight utilization, now includes the so-called three-phase method, which explicitly requires BSDF data. Such BSDF data are therefore essential in planning practice in simulations and normative procedures, but there is no standardized method for creating such data.

[1] Gonio-photometer PG2 by pab Consulting for Optics & Engineering. `http://www.pab.eu`

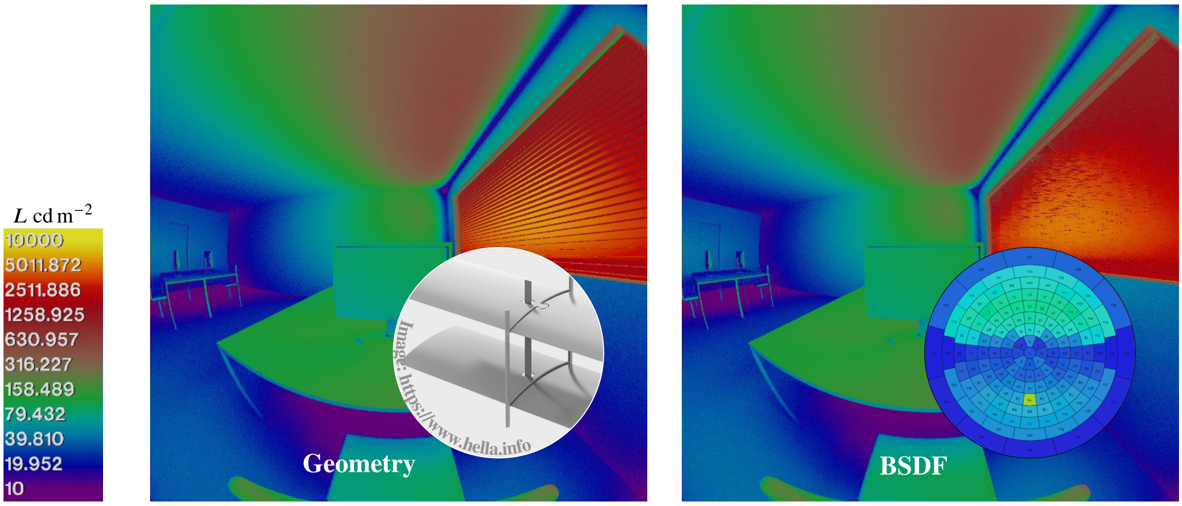

Fig. 2: Falsecolor images illustrating the luminance distribution in a room as derived from simulations using the geometry of venetian blinds (left) or using the corresponding BSDF representation (right).

2. Towards a New International Standard

2.1 Scope and Objectives

In order to close the gap in the standardization, the International Organization for Standardization (ISO) and the International Commission on Illumination (CIE) launched the project ISO/CIE DIS 25176 "Light and lighting - Daylight in buildings - BSDF data generation for complex fenestration systems" in 2024 as a joint effort.

The scope of the proposed standard is described as follows: *"This document specifies procedures (a) for characterizing angle-dependent transmittance and reflectance properties of complex fenestration systems (CFS) and (b) for generating tabular BSDF data sets from the measured or simulated data for use as input to simulation tools."* (ISO/CIE DIS 25176).

Therefore, ISO/CIE DIS 25176 aims to establish *'generally applicable methods for BSDF characterization of CFS for evaluation of performance criteria based on spatially resolved (luminance, solar patch) and/or integral radiation quantities (illuminance, solar irradiance) and thus on definitions and specifications for generating tabulated BSDF data. The subsequent derivation of analytical models in order to characterize some types of CFS with a large number of similar variations is not included in this document. Characterization of CFS as a function of wavelength (spectrally resolved) or position on a non-homogeneous surface is also not included in this scope.'* (ISO/CIE DIS 25176).

The targeted standard aims to ensure robust, comparable BSDF data as input for high-quality daylighting simulations, solar energy assessments, and for the method in ISO/CIE 10916. In terms of content, the standard is strongly aligned with a white paper prepared in 2021 by experts collaborating in the IEA SHC Task 61 / EBC Annex 77 (Geisler-Moroder et al., 2021). Rather than duplicating measurement standards, the standardization aims to harmonize methods and outputs for simulation and normative use.

2.2 Micro- and Macroscopic Complex Fenestration Systems

ISO/CIE DIS 25176 differentiates complex fenestration systems (CFS) into microscopic and macroscopic systems, based not on absolute geometric dimensions but with regards to a laboratories measurement capabilities. A laboratory's gonio-photometric setup defines the maximum sampling aperture, and thereby the maximum feature size when aiming for a representative average.

Microscopic systems are defined to be directly measurable with goniophotometers (e.g., roller shade fabrics and capillary structures, light scattering films), while macroscopic systems are assumed to be too large or irregular for direct measurement (e.g., most venetian or honeycomb blinds; facade layers comprising large-scale structures, i.e., horizontal and vertical fins or photovoltaic modules).

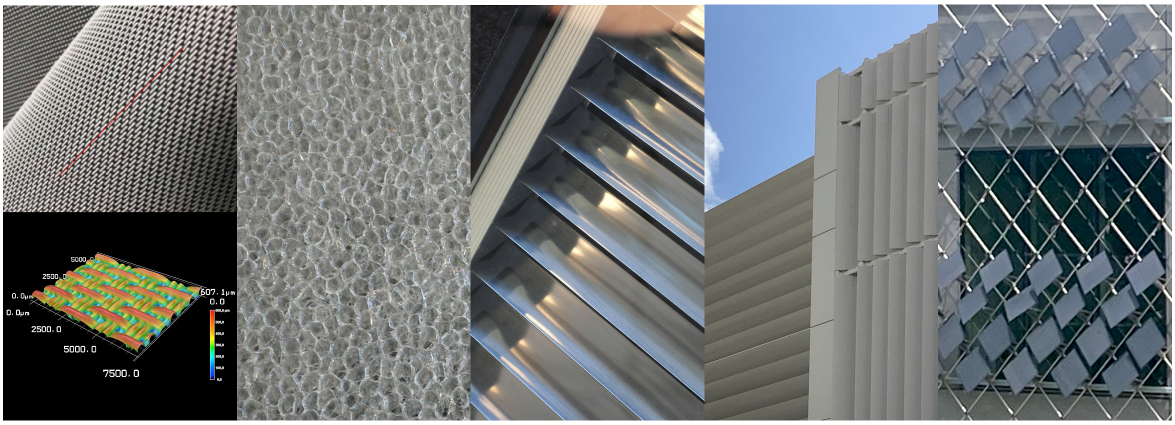

Fig. 3: Examples of microscopic and macroscopic CFSs, ranging from micro- to decimeters: Sunshade fabric (Ward et al., 2021), capillar translucent insulation, mirror-blinds, horizontal and vertical louvers, Adaptive Solar Facade (Nagy et al., 2016).

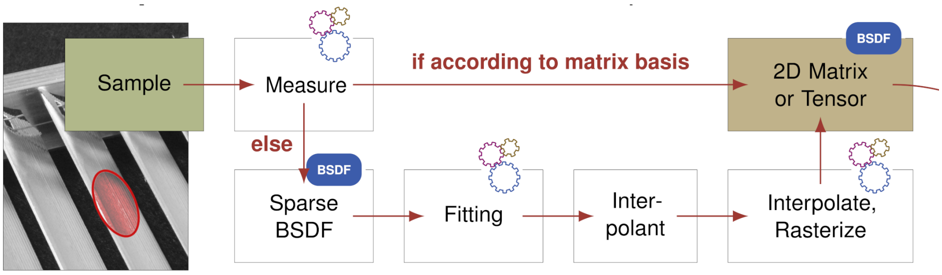

Fig. 4: Generation of BSDF data by gonio-photometric measurement on micro-structured CFSs. The standard describes a direct path from measurement to model, both employ the same directional basis (top), and a translation between the directional basis employed in the measurement to a target basis via interpolation and rasterizing (bottom).

Fig. 3 illustrates examples of such CFSs which are addressed by the standard, with periodical structures in the range of micro- to decimeters. It is important to emphasize that due to the different instruments in use, the systems characterized by moderate feature-sizes in the centimetre-range, e.g., the integrated mirror blinds shown in Fig. 3, may be considered microscopic in laboratories working with large sampling apertures, but macroscopic in others.

2.3 BSDF Generation Methods

ISO/CIE DIS 25176 recommends direct measurement when possible, e.g., in the case of microscopic CFS, when a representative BSDF of the system can be aquired. With regards to instrumentation and measurement, the document refers to existing standardised methods for the measurement of reflection and transmission, but suggests opportunities to reduce measurements, e.g., due to common symmetry properties of CFSs.

The direct measurement of the BSDF of microscopic CFSs produces a discrete set of data-points according to the employed directional basis. If that matches the basis of the target model, a direct translation into a simulation model is possible (Fig. 4, top). For all other cases, the standard recommends to measure a sparse BSDF data-set according to the particular properties of sample and instrumentation. This data-set is sparse, as not all combinations of incident and scattered directions defined by the target model's directional basis may be contained. Therefore, the measured data-points are first used to fit interpolants, that can then be sampled according to the target's directional basis (Fig. 4, bottom). This latter approach introduces additional complexity, but promises higher flexibility, i.e., since the measurement can make full use of the employed gonio-photometer's capabilities, refined models can be generated from the measured data at any time. Adapting the measurement's basis to the sample also allows to take into account that the BSDFs of many CFSs only gradually change with incident direction but require a dense set of scattered directions to account for pronounced peaks, e.g., due to specular transmission and reflection. Decreasing the number of incident directions can reduce the measurement effort significantly, and still produce a full, dense BSDF model when a suitable interpolation algorithm is employed (Ward et al., 2014).

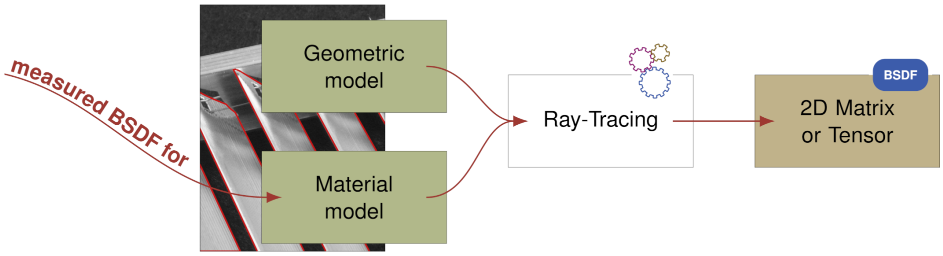

Fig. 5: Computational generation process for macroscopic CFSs by ray-tracing. The material models used in this approach can be generated in analogy to the measurement-based generation of BSDF applied to the modelling of microscopic CFSs.

An implementation in the open source lighting simulation environment Radiance allowed the thorough testing of this modelling technique, and demonstrated its applicability to typical daylight assessment problems (Ward et al., 2022).

For macroscopic systems, the standard recommends virtual, i.e., simulation-based gonio-photometry. Fig. 5 illustrates the work-flow. The simulation combines geometric 3D representations with reflection and transmission models. The latter can be general physics-based models or derived from measurements. Measurement-based models can be produced by a modelling workflow as described for microscopic CFSs. The irregular reflection properties of the textured surface of a CFS' element, for example, can be modelled by its measurement-based BSDF. Light propagation through the CFS can then be simulated by ray-tracing. One implementation in Radiance ray-traces random incident and scattered directions, and bins the results according to a regular directional basis. This basis can be that of the target model, allowing for direct formatting in a suitable matrix format, or an intermediate, high-resolution tensor that can then be compressed by adaptive data-reduction. The open-source implementation in Radiance has enabled researchers to test and validate also this method and its applicability (Ward et al., 2022).

The modelling of light scattering by BSDF as an average property rather than simulating light propagation through a geometric representation of CFSs offers great opportunities in terms of efficiency and general applicability. However, in the case of macroscopic CFS, the spatial averaging often results in a loss of visual information. Fig. 6 illustrates this for the case of Venetian blinds exposed to direct sunlight. Modelled by its corresponding BSDF, the slabs forming this CFS as well as the shadow-pattern they would cast become invisible (left). This averaging can be problematic in any contrast-based assessments, e.g., of glare and visual comfort. For such applications, ISO/CIE DIS 25176 suggests to embed 'proxy geometry', i.e., a geometric representation of the CFS, in the BSDF model. The light simulation can then evaluate the BSDF to solve light propagation into the assessed zone, but rely on the geometric model to render the system itself as well as direct transmission through it. Fig. 6 (right) shows how this approach can produce a visual representation of the CFS (red) as well as the shadow pattern it produces (blue), still relying on its effective BSDF for all other light transport calculations.

Again, ISO/CIE DIS 25176 focuses on an end-to-end workflow to represent the light scattering properties of macroscopic CFS: data collection, conversion to suitable BSDF discretizations, provision in XML-based formats, interpolation, optional validation through measurements of direct-hemispherical transmission, and embedding of proxy geometry. The standard addresses uniform versus peaky scattering, the importance of instrument signature, and incidence-direction sampling guided by sample symmetry.

2.4 Supplementary Content

ISO/CIE DIS 25176 comes with several informative annexes, that shall support and further guide the application of the standard. Several established directional bases are consistently described. One interpolation method for the suggested translation of sparse, discrete gonio-photometric measurements to a given directional basis, as well as the inclusion of proxy geometry are explained in detail. A procedure for model validation based on direct-hemispherical transmission is presented. Finally, the annexes include two detailed examples for the generation of BSDF models of micro- and macroscopic CFSs, i.e., fabric shades and Venetian blinds, in accordance with the proposed standard.

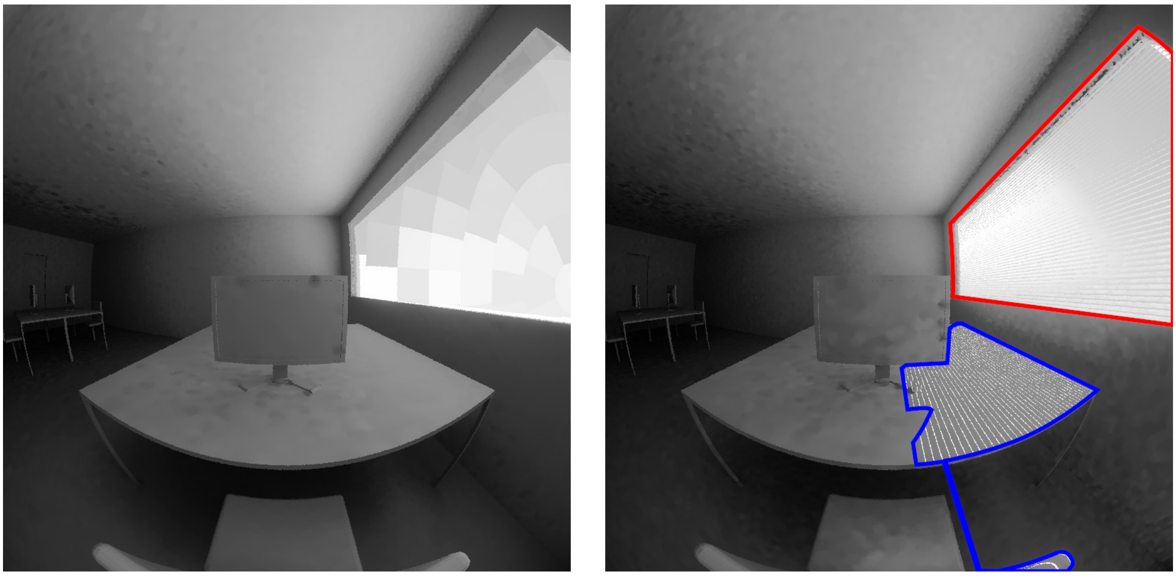

Fig. 6: Embedding of a geometric proxy for refined modelling of direct transmission. Left: Venetian Blinds modelled by BSDF. Note the visible patch-artefacts of the Klems basis, and the lack of shadow-patterns by the louvers. Right: Same BSDF model, but with embedded proxy-geometry. The latter is evaluated when looking directly at the CFS (red), and for direct sunlight (blue image region).

3. Discussion and Outlook

The previous work in IEA SHC Task 61 / EBC Annex 77, that had led to a white paper (Geisler-Moroder et al., 2021) and defined a clear pathway (Geisler-Moroder et al., 2024), enabled rapid consensus for a first draft of the proposed standard. By now, ISO/CIE DIS 25176 has reached the status of a Draft International Standard (DIS) and has been available for comment in the second and third quarter of 2026 (Fig. 7). Experts in the field of BSDF data generation and interested parties were invited to participate and provide feedback via their respective national committee of ISO TC 274 or their national CIE committee. Depending on the submitted comments, it is hoped that the draft can be revised accordingly, so that the process can be finalized with the planned publication of the international standard in mid 2027.

ISO/CIE DIS 25176 is intended to fill a gap in the current body of norms and standards. The proposed standard shall formally define models that are required for methods already specified in existing standards, i.e., the three-phase method included in ISO/CIE 10916:2024. With a strict focus on the preparation of BSDF data-sets, the authors of the draft aimed to avoid overlaps with existing standards, e.g., in the areas of optical metrology or performance assessments.

The proposed standard extends daylight assessment and simulation standards to include reliable, comparable BSDF data generation, supporting both CFS development and application. It is hoped that the proposed ISO/CIE DIS 25176, by guiding laboratories in parametrizing BSDF procedures based on intended use and CFS characteristics, will also be beneficial for industry, planners, and consultants employing the resulting models. Furthermore, the proposed standard is hoped to reduce documentation effort through the definition of a consistent terminology and practical examples, that can be referred to.

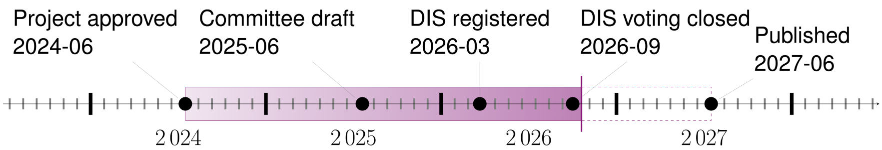

Fig. 7: Progress of the standardization process as of September 2026.

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References

Apian-Bennewitz, P., 2025. Characterization of window materials using out-of-plane BSDF measurements, combining resolution of small-angle scattering and low level background scattering, in: Harding, K.G., Zhang, S., Hyun, J.S., Li, B., Marrugo, A.G. (Eds.), Dimensional Optical Metrology and Inspection for Practical Applications XIV, SPIE. p. 134620A. doi:10.1117/12.3054183.

Apian-Bennewitz, P., de Boer, J., Bueno, B., Deroisy, B., Fang, Y., Geisler-Moroder, D., Grobe, L.O., Jonsson, J.C., Lee, E.S., Tian, Z., Wang, T., Ward, G.J., Wilson, H.R., 2021. Analysis and evaluation of BSDF characterization of daylighting systems. white paper T61.C.2.2. International Energy Agency SHC Task 61. doi:10.18777/ieashc-task61-2021-0012.

Bashir, F.M., Dodo, Y.A., Mohamed, M.A.s., Norwawi, N.M., Shannan, N.M., Afghan, A.A., 2024. Effects of natural light on improving the lighting and energy efficiency of buildings: toward low energy consumption and co2 emission. International Journal of Low-Carbon Technologies 19, 296–305. doi:10.1093/ijlct/ctad130.

De Michele, G., Loonen, R., Saini, H., Favoino, F., Avesani, S., Papaiz, L., Gasparella, A., 2018. Opportunities and Challenges for Performance Prediction of Dynamic Complex Fenestration Systems (CFS). Journal of Facade Design and Engineering 6, 101—-115. doi:10.7480/jfde.2018.3.2531.

Geisler-Moroder, D., Lee, E., Ward, G., Bueno, B., Grobe, L.O., Wang, T., Deroisy, B., Wilson, H.R., 2021. BSDF generation procedures for daylighting systems. white paper T61.C.2.1. International Energy Agency SHC Task 61. doi:10.18777/ieashc-task61-2021-0001.

Geisler-Moroder, D., Lee, E.S., Apian-Bennewitz, P., de Boer, J., Bueno, B., Deroisy, B., Fang, Y., Grobe, L.O., Hauer, M., Hoffmann, S., Jonsson, J.C., Maurer, C., Plörer, D., Subramaniam, S., Tian, Z., Wang, T., Ward, G.J., Weitlaner, R., Wilson, H.R., 2024. BSDF data generation for daylight applications: A call for international standardization. Lighting Research & Technology 57, 14771535241291838. doi:10.1177/14771535241291838.

Grobe, L.O., 2018. Characterization and data-driven modeling of a retro-reflective coating in radiance. Energy and Buildings 162, 121–133. doi:10.1016/j.enbuild.2017.12.029.

IEA SHC Task 61, 2019. Daylighting of non-residential buildings: Position paper. Technical Report. International Energy Agency Solar Heating and Cooling Programme. URL: https://task50.iea-shc.org/Data/Sites/1/publications/IEA-SHC-Daylighting-Non-Residential-Buildings-Position-Paper.pdf. accessed online 14th September 2026.

ISO/CIE 10916:2024, . Light and lighting – Energy performance of lighting in buildings – Calculation of the impact of daylight utilization. (Standard). International Organization for Standardization. Geneva, Switzerland.

ISO/CIE DIS 25176, . Light and lighting — Daylight in buildings -— BSDF data generation for complex fenestration systems. (Standard). International Organization for Standardization. Geneva, Switzerland. URL: https://www.iso.org/standard/89258.html. (Accessed online 13th March 2026).

Jamrozik, A., Clements, N., Hasan, S.S., Zhao, J., Zhang, R., Campanella, C., Loftness, V., Porter, P., Ly, S., Wang, S., Bauer, B., 2019. Access to daylight and view in an office improves cognitive performance and satisfaction and reduces eyestrain: A controlled crossover study. Building and Environment 165, 106379. doi:10.1016/j.buildenv.2019.106379.

Kajiya, J.T., 1986. The rendering equation. SIGGRAPH Computer Graphics 20, 143–150. doi:10.1145/15886.15902.

Knoop, M., Stefani, O., Bueno, B., Matusiak, B., Hobday, R., Wirz-Justice, A., Martiny, K., Kantermann, T., Aarts, M., Zemmouri, N., Appelt, S., Norton, B., 2020. Daylight: What makes the difference? Lighting Research & Technology 52, 423–442. doi:10.1177/1477153519869758.

Lee, E.S., Matusiak, B.S., Geisler-Moroder, D., Selkowitz, S.E., Heschong, L., 2022. Advocating for view and daylight in buildings: Next steps. Energy and Buildings 265, 112079. doi:10.1016/j.enbuild.2022.112079.

Nagy, Z., Svetozarevic, B., Jayathissa, P., Begle, M., Hofer, J., Lydon, G., Willmann, A., Schlueter, A., 2016. The adaptive solar facade: From concept to prototypes. Frontiers of Architectural Research 5, 143–156. doi:10.1016/j.foar.2016.03.002.

Stover, J.C., 2025. Optical Scattering: Measurement and Analysis. Fourth ed., SPIE Press, Bellingham WA, United States. doi:10.1117/3.100366.

Wang, T., Lee, E.S., Ward, G.J., Yu, T., 2023. Field validation of isotropic analytical models for simulating fabric shades. Building and Environment 236, 110223. doi:10.1016/j.buildenv.2023.110223.

Ward, G., Kurt, M., Bonneel, N., 2014. Reducing anisotropic bsdf measurement to common practice, in: Proceedings of the Eurographics 2014 Workshop on Material Appearance Modeling: Issues and Acquisition, Eurographics Association. pp. 5–8. doi:10.2312/mam.20141292.

Ward, G.J., Bueno, B., Geisler-Moroder, D., Grobe, L.O., Jonsson, J.C., Lee, E.S., Wang, T., Rose Wilson, H., 2022. Daylight simulation workflows incorporating measured bidirectional scattering distribution functions. Energy and Buildings 259, 111890. doi:10.1016/j.enbuild.2022.111890.

Ward, G.J., Wang, T., Geisler-Moroder, D., Lee, E.S., Grobe, L.O., Wienold, J., Jonsson, J.C., 2021. Modeling specular transmission of complex fenestration systems with data-driven bsdfs. Building and Environment 196, 107774. doi:10.1016/j.buildenv.2021.107774.