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Cloud-Based Semantic Structures, Verified Models and Advanced Experimental Methods for Optical and Thermal Characterization of Building Envelopes and their Components, including those inaccessible to current methods

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Cloud-Based Semantic Structures, Verified Models and Advanced Experimental Methods for Optical and Thermal Characterization of Building Envelopes and their Components, including those inaccessible to current methods

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Abstract

of the ICON project on “Cloud-Based Semantic Structures, Verified Models and Advanced Experimental Methods for Optical and Thermal Characterization of Building Envelopes and their Components, including those inaccessible to current methods”

LBNL and Fraunhofer ISE collaborated within this ICON project to support the global construction industry by achieving the following goals:

- **Development of a cloud-based, BIM-compatible, internationally recognized data base** for architectural glazing, daylighting, solar-shading and active-solar (i.e. building-integrated PV and solar-thermal) components **(WP2)**. All data formats, data files and access specifications are “open”.
- **Development of validated measurement and data-processing methods to determine the full range of solar-optical properties of advanced building-envelope products (WP4)**
- **Implementation of joint strategies for the population of the new database** with manufacturer data sets certified by independent labs **(WP3)**. This included the establishment of Fraunhofer ISE as the European regional data aggregator (responsible for database input from Europe) for the new and existing international data bases.
- **Development of accurate component and systems-level daylight and energy simulation programs for product labeling, design optimization and building planning** that treat the optical and thermal characteristics of advanced building envelope components accurately and can interface via well-defined API or other semantic web-approaches with the new database for building envelope components **(WP1)**.
- **Development of simple but sufficiently accurate methods for the initial design phase and building permit application** to represent the optical, thermal and energy-relevant properties of architectural glazing, solar-shading and active-solar products and integrated design solutions **(WP5)**. These tools will also communicate with the new database via semantic web interfaces.

Executive Summary

Collaboration between LBNL and Fraunhofer ISE within this ICON project has resulted in the team achieving the central objectives of defining new BIM-compatible, structured formats for measured optical product data, and conceiving and implementing new validated and documented tools and measurement procedures for complex fenestration systems and components.

Within WP1, on "**Enhanced component and building energy simulation programs for complex fenestration**", standards for calculating the heat transfer through fenestration systems were reviewed. This involved comparing the ISO 15099, ISO EN 52022-1 and ISO EN 52022-3 standards, and the implementation of ISO 15099 in different building simulation programs. Based on independent implementations of ISO 15099 into tools by LBNL and Fraunhofer ISE, the sensitivity of the thermal performance of window attachments to their features was studied. Methods and representations of complex fenestration systems for dynamic glare evaluation were benchmarked. Results, based on calculating the vertical illuminance and the Daylight Glare Probability (DGP) index from BSDFs of different resolution, indicate that the combination of low-resolution BSDF and peak extraction outperforms the use of high-resolution BSDF for idealized fabrics. A Python library, the software tool frads, was developed to automate various Radiance simulation workflows, including support for a workflow involving high-resolution BSDF. A joint review of simulation workflows for energy, daylighting and glare analysis based on data-driven bi-directional scattering distribution functions (BSDFs) has been published in a peer-reviewed journal. WINDOW 7.8 was updated to integrate normal-normal and normal-diffuse spectra of the type measured in the inter-laboratory comparison (ILC) for light-scattering glazing of WP4. The open-source WinCalc program has been updated and posted on GitHub and standardized API was developed for integration in third party software tools. An open-source Python script PyWinCalc was developed as an implementation of WinCalc API and with communication with the cloud-based IGSDB (International Glazing and Shading Database) to perform calculations of optical and thermal window properties. PyWinCalc is also posted as an open source code on GitHub. The next generation of WINDOW and THERM tools (version 8) was initiated during the ICON project and an alpha version of these tools is posted at: https://windows.lbl.gov/therm-8-window-8. WINDOW8 uses the WinCalc engine and accesses the cloud-based IGSDB.

WP2, in addressing "**BIM-compatible virtual complex fenestration (CF) components and data base**", achieved the central objective of defining new BIM-compatible, structured formats for measured glazing and shading product data with its definition of the metabase[1] (formerly referred to as IKDB - ICON Knowledge Data Base) structure. Detailed JavaScript Object Notation (JSON) schema

[1] Metabase" is the name for a database which manages unique identifiers for components and institutions. It is required to facilitate the search for the data of a component across product databases. The metabase has a back end which is accessible only via its API. This is the best way for software developers to interact with the network of product databases. The metabase also has a front end which is accessible via www.buildingenvelopedata.org. This is helpful especially for people outside the IT branch who want to access information about a specific component.

for measured optical and descriptive product data have been implemented, including refinement after feedback from industry experts from the European Solar-Shading Organization (ES-SO). A data schema for optical data sets was developed and posted open-source on GitHub, which facilitates automated exchange of data by ensuring that the request to servers and the answers of servers are specified well and can be validated automatically. An operational version of the metabase has been created, based on definition of the most important keys of the data schema for building envelopes, construction of the domain model of the metabase, including universally unique identifiers (UUIDs), and definition of the layers of the metabase. In parallel, a cloud-based database, IGSDB (International Glazing and Shading Database) for glazing and shading data has been developed to the stage where an alpha version of the IGSDB, including glazing data, was developed and posted on the heroku cloud server (Checkertool-staging.herokuapp.com and igsdb.lbl.gov). Implementation of JSON schema and GraphQL API for the communication with the metabase was developed for the IGSDB and the functionality has been demonstrated through the series of test records. Future implementation of the metabase JSON schema and API in the ES-SO ESDA database is being discussed with ES-SO partners. Ultimately, the metabase will serve as an umbrella database that connects product data globally.

Establishment of **Fraunhofer ISE as the Regional Data Aggregator RDA for NFRC in Europe** has been accomplished within WP3. In 2020 the first contract between NFRC and Fraunhofer ISE as the European RDA was executed. In 2021, a second installment of the contract was commenced and progress is being tracked through the online spreadsheet that encompasses the North American and Euroepan RDA’s at this time.

Within WP4, on “**Optical measurement and data-processing methods applying bi-directional data**”, efforts to validate optical measurement procedures concentrated on conducting an inter-laboratory comparison exercise (ILC) for NFRC to validate integrating sphere measurements of diffuse glazing samples, using spheres with sufficiently large sample apertures. The good agreement achieved among the participants validated the defined instruments and procedures and provided a basis for specifying acceptable tolerances on measurement results, representing a significant improvement on the previous situation with unsuitable integrating spheres for this type of sample. Both the procedures and the tolerances have been accepted by the NFRC membership as modifications to NFRC technical documents. Concerning photogoniometric measurements to obtain bi-directional data, an experimental procedure and data post-processing to correct for a dark signal have been implemented. A new metric has been defined for concise presentation of bi-directional scattering distribution function (BSDF) results. Recommendations on BSDF generation procedures and applications for glare analysis have been documented in a white paper on this subject that has been published as a technical report within IEA-SHC Task 61. A second Technical Report on the analysis and evaluation of BSDF characterization of daylighting systems has been published within the same Task.

Activities within WP5 on “**Inclusion of newly developed complex fenestration properties in widespread applications (dissemination)**” have ensured that the ICON research activities and results are disseminated beyond the immediate ICON project team. These include ongoing consultation with ES-SO (European Solar-Shading Organization) and AERC (North American window Attachment Energy Rating Organization), NFRC (National Fenestration Rating Council) and presentations of measurement procedures and calculation tools to glazing and solar-shading industrial associations, and to professional bodies for building planners and architects, in both Europe and the U.S.A. With completion of the ICON project, dissemination activities will focus on reaching commercial players, starting with a webinar in conjunction with the final ICON meeting which is hosted by ES-SO and directed toward technical representatives of the solar-shading industry in Europe, the USA and Australia. Methods developed in this project have been included in ASHRAE Fenestration Technical Committee TC 4.5, under the Calculation Procedures Subcommittee (ASHRAE = American Society of Heating, Refrigerating and Air-Conditioning Engineers). A proposal for the update of ISO window standards was developed as a NWI (new work item) and will be proposed to ISO TC163. These dissemination activities have already created or reinforced contacts with commercial clients, leading to contract research based on the results obtained within the ICON project.

It is the intention of the ICON project partners to continue the successful collaboration of the ICON project, both by generating new frameworks themselves and also by co-operating within frameworks offered by external organisations.

Content

1 Introduction

This ICON project had the central objectives of defining new BIM-compatible, structured formats for measured optical product data, and conceiving and implementing new validated and documented tools and measurement procedures for complex fenestration systems and components.

In detail, the objectives as documented in the Statement of Work, §2.1(j) are listed below, with the current status inserted for each one.

<u>Short-term scientific and dissemination objectives (during ICON project)</u>:

- Conception and implementation of new validated and documented measurement procedures for complex fenestration systems and components
    - completed for integrating sphere measurements of light-scattering glazing and photo-goniometric measurement for daylighting and glare-protection evaluation of textiles
- Definition of new BIM-compatible, structured formats for measured product data satisfying identified product usage requirements
    - metabase structure defined and detailed JSON schema for measured and descriptive product data implemented, including refinement after feedback from industry experts (ES-SO)
- Presentation of these measurement procedures and data formats to glazing and solar-shading industrial associations in Europe and the U.S.A.
    - high-level presentations at meetings of ICG-TC10 (International Commission on Glass – Tech. Comm. 10), Bundesverband Flachglas (BF - German Architectural Glazing Association), NFRC (National Fenestration Rating Council in North America), ASHRAE (American Society for Heating Refrigerating and Air-Conditioning Engineers), and to ICON industry experts from ES-SO (European Solar-Shading Organisation) and AERC (Attachments Energy Rating Council in the USA)
- Establishment of Regional Data Aggregator (RDA) scheme for IGDB and CGDB, implementation of LBNL as RDA for North America and Fraunhofer ISE for Europe.
    - Established for IGDB.
    - Assessed but deemed inappropriate for CGDB.
- Presentation of the RDA status of Fraunhofer ISE to European glazing and shading trade organizations
    - RDA status for NFRC presented to ICG-TC10, BF and NFRC members

Mid-term scientific and dissemination objectives (at end of ICON project):

- Revision and extension of building-envelope component and building-energy simulation tools to exploit advantages of BIM-compatible data formats in cloud-based data base
  - information on API requirements to allow data transfer/access documented
  - models developed and software tools with defined API for modeling glazing, shading and whole windows provided as open source tools
  - interface based on JSON schema between metabase and IGSDB implemented
- Establishment of RDA scheme for new data base from ICON project, implementation of LBNL as RDA for North America and Fraunhofer ISE for Europe.
  - Objective modified: RDAs will be for the IGSDB, which is accessible both directly and via the metabase. Implementation of RDA structure for the IGSDB is in progress but not completed.
- Documented tools, algorithms and/or proposals for standards for product characterization, the initial building design phase and building permit application
  - modifications to NFRC 300, 301, 302 for light-scattering glazing introduced and accepted by NFRC
  - proposal to CEN TC 129, WG 9 to adopt similar modifications to EN 410 relating to light-scattering glazing
  - FENER tool for the design and evaluation of innovative fenestration systems and their control
  - ISO new work item proposal for updated calculation algorithms for windows and window shading systems
  - documentation of workflows for measuring BSDFs for use in daylighting and glare assessment in a report of IEA-SHC T61
  - documentation of daylight simulation workflows incorporating BSDFs in a paper published in the peer-reviewed journal, Energy & Buildings
- Presentation of these tools and workflows to professional bodies for building planners and architects in Europe and the U.S.A.
  - at Building Simulation 2019 of IBPSA, September 2019
  - at Building Simulation 2021 of IBPSA, September 2021

Long-term scientific and dissemination objectives (after the ICON project):

- Continued operation and population of data bases as RDA's for North America and Europe (LBNL and ISE, respectively)
    - RDA contracts with NFRC have been extended beyond the end of the ICON project and can be expected to be renewed on an annual basis.
- Joint ISE-LBNL projects with internationally active industrial partners in building-envelope product projects applying the results of WP 1 to WP 4
    - The objective is unchanged; the basis for such projects has improved as a result of the ICON project, not only because of the experience gained in scientific collaboration but also in overcoming trans-Atlantic legal barriers
- Joint ISE-LBNL projects with internationally active industrial partners in building construction projects applying the results of WP 1 to WP 4
    - The objective is unchanged; the basis for such projects has improved as a result of the ICON project, not only because of the experience gained in scientific collaboration but also in overcoming trans-Atlantic legal barriers
- Cooperation with Fraunhofer CSE, Boston, to support European manufacturers of glazing and shading technology seeking entry to the U.S. market
    - objective no longer applicable, as Fraunhofer CSE has closed
- Introduce characterization and calculation procedures for building-envelope components and building energy performance into standards, ratings and metrics, with the long-term goal of achieving global harmonization
    - The objective is unchanged. It is recognized that the chances of success are greater with regard to procedures that are newly introduced, like the recently approved ISO 19467 addressing laboratory determination of SHGC, than with similar but non-identical standards that are already well established in the USA and Europe, e.g. for emissivity determination.

2 Collaboration: Review and status

The collaboration between the two partners within the duration of the ICON project was maintained by the following measures:

- Regular monthly conference calls of all project and WP leaders
- More frequent conference calls and email correspondence among the members of individual WPs
- In the second half of the project, fortnightly meetings and frequent interaction between the Fraunhofer programmers and the LBNL programming team as part of the WP2 work
- Joint participation in conference calls with the representatives of the European, U.S. American and Australian shading manufacturers' associations, ES-SO, AERC and BMAA, respectively
- Joint participation in IEA-SHC Task 61 on Daylighting
- Joint participation in or mutual representation at meetings of NFRC in the USA and ICG-TC10 in Europe
- Face-to-face meetings in Freiburg during the week including the kick-off meeting in May 2019, in Berkeley for a week in July/August 2019, and in Freiburg for a week in February 2020. At each of these meetings, significant progress was made in each work package and the opportunity was also taken to liaise with local industry experts (NFRC and AERC in the USA and ES-SO in Europe). The global Covid pandemic unfortunately prevented any further travel for face-to-face meetings but the working basis established there was important for further fruitful collaboration via electronic media.

2.1 Key scientific collaborative achievements

Based on the collaboration within WP1 and WP4, both partners have contributed within IEA SHC Task 61 to one Technical Report as a White Paper on BSDF generation procedures for daylighting systems and a second Technical Report on analysis and evaluation of BSDF characterization of daylighting systems. This collaboration also led to publication of a joint paper on daylight simulation workflows incorporating BSDFs in the peer-reviewed journal, Energy & Buildings.

- Review of the current state of the art in the field of measurement and simulation characterization of daylighting systems by bidirectional scattering distribution functions (BSDFs), and definition of commonly used BSDF data resolutions.
- Review of empirically based procedures for generating BSDF data sets for façade systems for later use in lighting simulation software.
- Recommendations for adequate characterization methods and BSDF resolutions for different classes of systems: transparent systems, homogeneous or small pattern diffusing systems,

diffuse or specular blinds and grids, macroscopic prismatic systems, and micro- or nano-structured systems.

- A review of simulation workflows for energy, daylighting and glare analysis based on data-driven bi-directional scattering distribution functions (BSDFs).
- A benchmark of state-of-the-art methods for annual glare analysis in terms of computational time (CPU time) and accuracy.
- Strategies to reduce the computational time of glare calculations without compromising the accuracy of glare calculations. Different Radiance-based methods are applied, and analytical isotropic fabric systems are parametrized in terms of specular/diffuse scattering components and cut-off angle.

The WinCalc stand-alone calculation engine for thermal and optical calculations was completed and published as an open-source code on GitHub as well as a python script (PyWinCalc), which utilizes WinCalc API and allows users to run parametric simulations from the command line. This development was accomplished by LBNL, which kept Fraunhofer ISE updated on these developments. This engine includes state-of-the-art calculation procedures and is available to third party software developers to include in their GUIs and web tools. The frads Python library was developed to automate various Radiance simulation workflows, including support for a workflow involving high-resolution BSDF.

Within WP2, collaboration resulted not only in consensus on the JSON schema for the metabase. A JSON data schema for optical data sets was developed by Fraunhofer ISE and posted open-source on GitHub. LBNL developers of the IGSDB implemented an API in the language GraphQL to facilitate communication with the metabase. The IGSDB is gradually replacing current glazing (IGDB) and shading (CGDB) databases and has been interfaced into WINDOW 8, where it will serve as a core database for both glazing and shading products.

The NFRC inter-laboratory comparison on measuring light-scattering glazing for WP4 was prepared, conducted, analysed and reported by both partners together. Similarly, the results on experimental aspects of BSDF determination presented in the two reports within IEA-SHC Task 61 benefited from the collaborative discussions. The dissemination activities of WP5, which officially began in December 2019, have been undertaken both by mutual representation of the non-local partner and in joint publication and presentation of ICON results (as itemized above in Section 1).

2.2 Key market-oriented collaborative achievements

A workflow that can be easily implemented in building simulation programs in order to perform annual glare risk assessments based on the Daylight Glare Probability (DGP) method. The DGP method has been used in the preparation of the European Daylighting Standard EN 17037 to recommend glare protection classes of shading devices for different situations (climate, façade orientation, window size, view position and direction). By implementing the DGP method, building simulation programs can be used to make design decisions on conflicting functions of fenestration systems, including glare protection. A case study is presented to illustrate the proposed workflow.

In WP3, Fraunhofer ISE is now established as the Regional Data Aggregator (of glazing optical properties) for Europe, thanks to the mediation by LBNL with NFRC. This facilitates data submission for European glazing manufacturers with sales in the USA, supporting their commercial activities there.

2.3 Perspectives

Fraunhofer ISE and Fraunhofer ISE have collaborated, with the support of LBNL, component manfacturers and software to developers, to prepare a research project sketch to “Improve the Quality and Cost-Benefit Ratio of Building Envelopes by Providing Product Data Efficiently and Using it in Software to Support their Planning“ (EQWIN-P). It has been submitted to the German Federal Ministry for Economic Affairs and Climate Action (BMWK) for evaluation.
The ICON team has prepared a “Request for Proposal” (RFP – call for bids) for presentation at the NFRC Spring Meeting 2022, which aims to introduce an indoor method to determine the Solar Heat Gain Coefficient (SHGC), which is based on ISO 19467, into the NFRC framework. This would widen the options to glazing manufacturers to determine the SHGC, a characteristic that is increasingly demanded for building-energy rating and building approvals.

Discussion will continue on still open issues in BSDF characterization of daylighting systems and their application in lighting simulation tools.

With completion of the ICON project, dissemination activities will focus on reaching commercial players, starting with the ES-SO-hosted webinar immediately following the final ICON meeting. It is directed toward technical personnel of the solar-shading industry in Europe, the USA and Australia.

More details on future plans for collaboration can be found in Section 5.

2.4 Challenges to cooperation

The hurdle of distance and a nine-hour time difference present ongoing challenges within this collaboration, which distinguish it from e.g. inner-European or internal U.S. project partnerships. However, the combination of intensive, whole-week face-to-face meetings and electronic communication, in addition to monthly web conferences between WP leaders and as-needed web conferences for different work packages, has proven to be effective in allowing good collaboration despite the barriers of time and space. The ICON team has published joint scientific publications, conference papers and technical reports, both without and with external co-authors, not only within an external “umbrella” such as the IEA.

A global challenge that significantly affected collaboration for the final two years of the ICON project is the global corona virus (SARS-CoV-2 virus). The last face-to-face meeting took place in February 2020; all further encounters have been via electronic media. Fortunately, the interpersonal communication basis was already well established and served us well during these two years. However, we hope that future collaboration will be able to include personal meetings.

3 Research: Collaborative work and results

Introduction to Chapter 3
As the concepts of the bidirectional scattering distribution function (BSDF) and some IT aspects of database structure are fundamental to the understanding of the reported work from WP1 and WP2, the corresponding sections begin with general introductions to these concepts, before the project results are presented. To avoid duplication, the reports on WP3, WP4 and WP5 concentrate on results obtained within the ICON project.

NOTE: Referenced publications which include results of work carried out within the ICON project are indicated with an asterisk (*).

3.1 WP1: Enhanced component and building energy simulation programs for complex fenestration

Contributors from Fraunhofer ISE: Bruno Bueno (WP leader), Abel Sepúlveda, Helen Rose Wilson
Contributors from LBNL: Eleanor Lee (original WP leader), Taoning Wang (WP leader since July 2019), Greg Ward, Jacob Jonsson, Stephen Czarnecki, Robin Mitchell, Charlie Curcija

Results anticipated from WP1 in Statement of Work (SoW): "Upgraded component and systems-level daylight and energy simulation programs for design optimization and building planning that treat the optical and thermal characteristics of light-scattering, light-redirecting and/or active-solar building envelope components accurately and can interface via well-defined API or other semantic web-approaches with the new database for building envelope components will be available. Such programs will accurately describe the impact of these building envelope components on the energy demand and visual comfort of a building."

3.1.1 Summary

The collaborative work between LBNL and Fraunhofer ISE in WP1 has led to several research contributions, which partially or completely cover the project's work plan for WP1. The optical and thermal methods implemented in current building simulation engines and interfaces have been reviewed, and both the simulation engines Radiance[1], WinCalc/PyWinCalc[2] and Fener[3], as well as the simulation interface WINDOW[4], have been further developed. In addition, gaps in other well-known building simulation tools have been identified. These gaps are mainly related to the use of Bi-directional Scattering Distribution Functions (BSDF) and assessment of glare risk. This section focusses

[1] https://windows.lbl.gov/software/radiance
[2] https://github.com/LBNL-ETA/Windows-CalcEngine
[3] https://fener-webport.ise.fraunhofer.de/
[4] https://windows.lbl.gov/software/window

on the effort invested within WP1 of the ICON project on the use and application of BSDF[1]. We propose simulation workflows that allow the use of BSDF in the prediction of daylighting provision, solar heat gains and glare risk in buildings. The proposed workflows are compatible with the experimental generation of BSDF as specified in WP4 and their storage for easy access as specified in WP2. This section also reports other collaborative activities not related to BSDF. A parametric study of energy performance for a range of shading products is presented. The comparison of the ISO 15099, ISO EN 52022-1 and ISO EN 52022-3 standards, and the implementation of ISO 15099 in different building simulation program, were described in the midterm report of the ICON project. Different window modeling methods for the EnergyPlus building energy simulation program were compared[2]. A summary of the Software developments carried out during the ICON project is presented at the end.

3.1.2 Introduction

BSDF describe the spatial distribution of light scattered by a sample in transmission and reflection (Figure 1) and are relevant for an accurate energy and daylighting evaluation of a daylit building space equipped with light-scattering fenestration systems. BSDF are well-defined optical representations of fenestration systems and can be experimentally determined with a photogoniometer, as specified in WP4. However, the experimental determination of BSDF leads to a large number of datapoints (as many as measured light scattering positions for a given incoming light direction, Figure 2). Typical BSDF datasets weigh between 100 and 1700 MB and are, therefore, difficult to interpret and visualize. A product comparison on the basis of these datasets becomes impracticable. This difficulty has led to a slow rate of assimilation of BSDF by the industry of shading devices, software developers and building façade planers, despite their potential. Based on the identification of this barrier, the research groups of LBNL and Fraunhofer ISE have generated a set of contributions that aim to:

- improve the understanding of BSDF[3*],
- develop and test standardized formats and representations of BSDF that can be used in simulation engines[4,*5*],

[1] NOTE: The term BSDF (bi-directional scattering distribution function) is used to describe many different things. Sometimes it is used to denote a file, sometimes it is used as shorthand when talking about a property which could be either BRDF (bi-directional reflectance distribution function) or BTDF (bi-directional transmittance distribution function). It is also used when talking about the discrete matrix representation of the continuous function.
[2] Kohler, C. ; Lyons, P.; Hart, R.G.; Curcija, D.C. 2019. “A Comparison of the Latest Window Modeling Methods in EnergyPlus.” 16th IBPSAS International Conference and Exhibition. 2-4 September, 2019. Rome, Italy
[3*] Geisler-Moroder, D., Lee, E.S., 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 - A Technical Report of Subtask C, IEA SHC Task 61 / EBC Annex 77. https://task61.iea-shc.org/publications. DOI: 10.18777/ieashc-task61-2021-0001
[4*] Geisler-Moroder, D., Ward, G.J., Wang, T., Lee, E.S., 2021. Peak extraction in daylight simulations using BSDF data. Proceedings of Building Simulation 2021, International Building Performance Simulation Association, Bruges, September 1-3, 2021.
[5*] Sepúlveda, A., Bueno B., Wang T., Wilson H.R.. Benchmark of methods for annual glare risk assessment. Building and environment 201 (2021), ISSN: 0360-1323. DOI: 10.1016/j.buildenv.2021.108006

- develop and test methods and workflows for the use of BSDF in energy, daylighting and glare simulation[3*,1*,2*], and
- develop methods and software tools that incorporate the methodology for modeling glazing, shading and whole window systems.

The relevant findings from the above-mentioned contributions are listed here:

- Review of the current state of the art in the field of measurement and simulation characterization of daylighting systems by bidirectional scattering distribution functions (BSDFs), and definition of commonly used BSDF data resolutions.
- Review of empirically based procedures for generating BSDF data sets for façade systems for later use in lighting simulation software.
- Recommendations for adequate characterization methods and BSDF resolutions for different classes of systems: transparent systems, homogeneous or small pattern diffusing systems, diffuse or specular blinds and grids, macroscopic prismatic systems, and micro- or nano-structured systems.
- A review of simulation workflows for energy, daylighting and glare analysis based on data-driven bi-directional scattering distribution functions (BSDFs).
- A benchmark of state-of-the-art methods for annual glare analysis in terms of computational time (CPU time) and accuracy.
- A peak extraction algorithm in Radiance to separate light transmitting peaks from the rest of BSDF data. The algorithm treats surface for sample ray as purely specular transmitting, i.e., transmit ray unperturbed, and then modifies by direct-direct transmission value in this
- direction computed from the BSDF data to avoid double-counting of near-specular transmission.
- Strategies to reduce the computational time of glare calculations without compromising the accuracy of glare calculations. Different Radiance-based methods, and analytical isotropic fabric systems are parametrized in terms of specular/diffuse scattering components and cut-off angle, are applied.
- A workflow that can be easily implemented in building simulation programs in order to perform annual glare risk assessments based on the Daylight Glare Probability (DGP) method. The DGP method has been used in the preparation of the European Daylighting Standard EN 17037 to recommend glare protection classes of shading devices for different situations

[1*] Ward G.J., Bueno B., Geisler-Moroder D., Grobe L.O., Jonsson J.C., Lee E.S., Wang T., Wilson H.R. Daylight Simulation Workflows Incorporating Measured Bidirectional Scattering Distribution Functions. Energy and Buildings, 259 (2022) 111890 https://doi.org/10.1016/j.enbuild.2022.111890

[2*] Bueno B., Sepúlveda A., Maurer C., Wacker S., Wang T., Kuhn T.E., Wilson H.R.. Easy-to-Implement Simulation Strategies for Annual Glare Risk Assessments based on the European Daylighting Standard EN 17037. Proceedings of Building Simulation 2021, International Building Performance Simulation Association, Bruges, September 1-3, 2021.

(climate, façade orientation, window size, view position and direction). By implementing the DGP method, building simulation programs can be used to make design decisions on conflicting functions of fenestration systems, including glare protection. A case study is presented to illustrate the proposed workflow.

- Discussion on still open issues in BSDF characterization of daylighting systems and their application in lighting simulation tools.

The following sections provide an overview of some important aspects regarding BSDF. After that, a parametric study of energy performance for a range of shading products is presented. This section closes with a review of software developments carried out during the project.

3.1.3 BSDF Representations and Formats

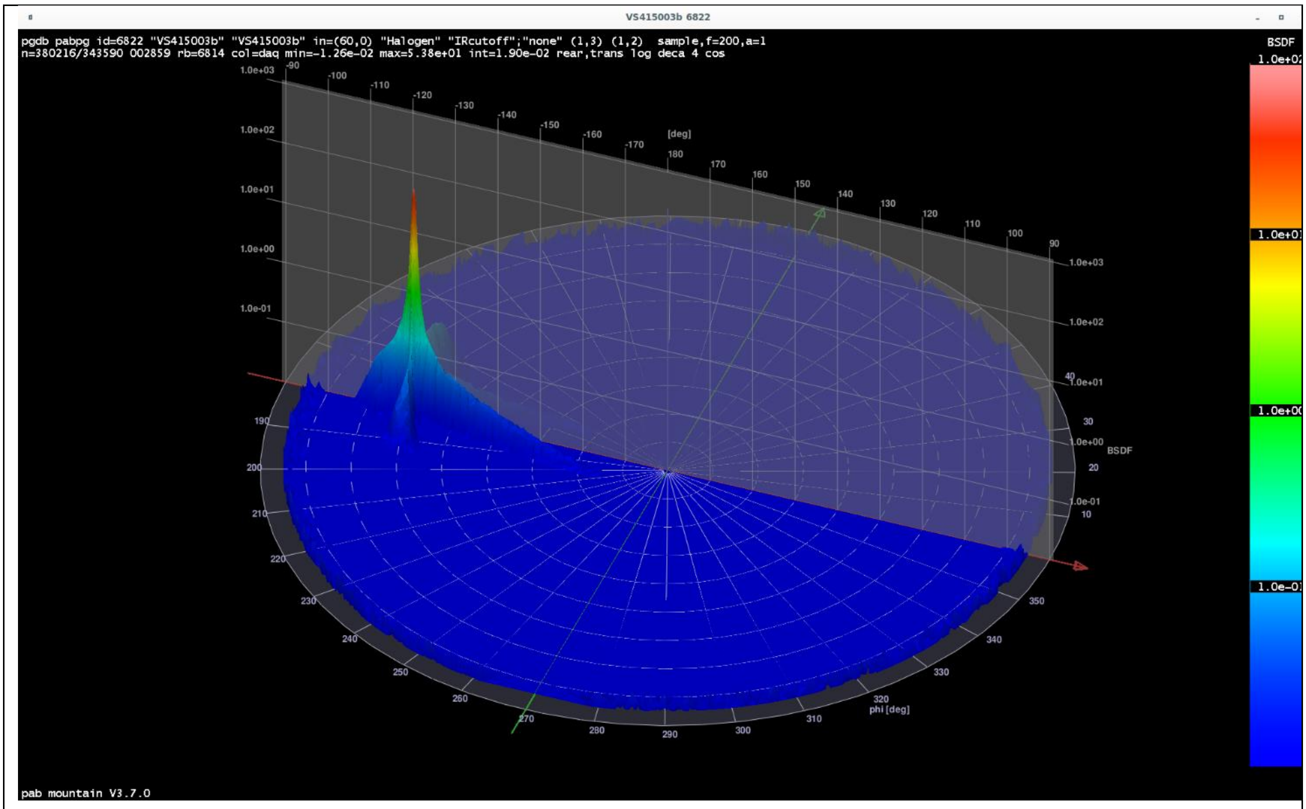


Figure 1 Bidirectional transmittance distribution function (BTDF) plotted for incident direction $\theta_i = 60°$, $\phi_i = 0°$. The transmission distribution is generated from goniophotometer data for a woven fabric shade. The sample was mounted such that the warp yarns were parallel to $\phi_i = 0°$.

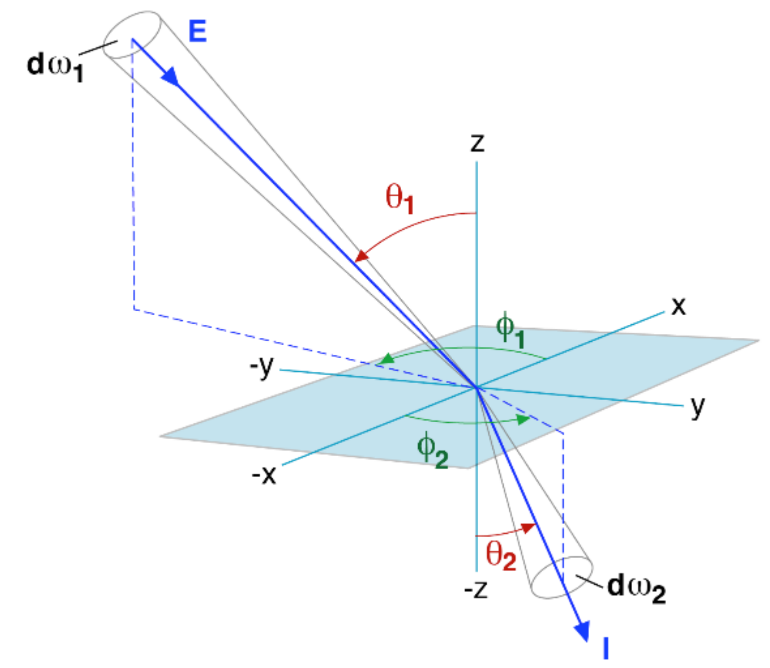


Figure 2 Incoming and outgoing angles of transmission relative to the sample material (shown as a blue plane). Source: LBNL.

Tabulated BSDF are specified via a discrete set of values for a defined number and set of directions (θ_1, ϕ_1; θ_2, ϕ_2, Figure 1 and Figure 2). As an example, they can be generated from discrete measured BSDF data by using an interpolation model[1]. The resolution of measured and tabulated BSDF data needs to match the optical properties of the represented system and the respective application. In the ICON project, we differentiate between low-resolution BSDF such as Klems (Figure 3) and high-resolution BSDF such as tensor-trees (Figure 4). Tensor-trees allow high-resolution representation of peaky areas in the exiting direction while keeping the overall data set reasonably small[2]. Currently, LBNL WINDOW enables generation of BSDF data with the Klems format. Within the Radiance BSDF library, the Klems and tensor-tree BSDF formats are supported and can be generated with the *genBSDF* tool. The Radiance programs *pabopto2bsdf*, *bsdf2klems* and *bsdf2ttree* allow the conversion of experimental BSDF datasets into Klems and tensor-tree BSDF to be used in simulation programs. The XML file format used for Klems and tensor-tree BSDF is described in Section 6.4. of the WINDOW 6.1 / THERM 6.1 Research Version User Manual (see section 3.4.4.1).

[1] Ward, G., Kurt, M., Bonneel, N. (2014), Reducing anisotropic BSDF measurement to common practice. Proceedings of the Eurographics 2014 Workshop on Material Appearance Modeling: Issues and Acquisition (MAM '14).
[2] Ward, G., Kurt, M., Bonneel, N. (2012). A Practical Framework for Sharing and Rendering Real-World Bidirectional Scattering Distribution Functions. DOE/LBNL Technical Report LBNL-5954E.

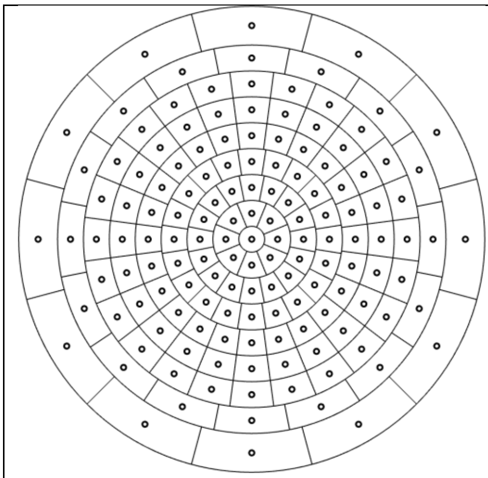


Figure 3 Klems BSDF angular basis for incident / exiting hemispheres.

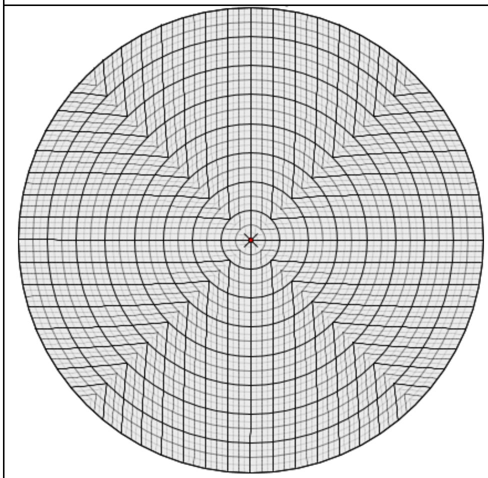


Figure 4 Example Shirley Chiu / Tensor tree angular basis with basis resolution of 4096 patches.

3.1.4 BSDF for daylighting calculations

BSDF can be used in daylighting simulations in two ways:

- For point-in-time simulations, directly in the ray-tracing process as a material description, or
- For annual daylighting calculations, in matrix form.

In both applications, low resolution BSDF data (e.g., resolved following the Klems basis) provide fast, approximate results.

When used in matrix form, tabulated BSDF representations can represent in-plane (e.g., Venetian blinds) and out-of-plane (e.g., awning) shading systems and can be used in three-, four-, five-, and six-phase methods to model the flux transfer through these systems[1]. The matrix-based methods

[1] Subramaniam S. Daylighting Simulations with Radiance using Matrix-based Methods. https://www.radiance-online.org/learning/tutorials/matrix-based-methods

started with the two-phase, or daylight coefficient method, where the relationship between the discretized sky luminance and indoor illuminance points is stored as a matrix, which is then used to compute any indoor illuminance by multiplying it with a vector of the real sky luminance value. With two-phase method, the shading systems are traced in-scene, which means changing shading systems require recomputing the entire matrix. The two-phase method was later extended by breaking down the flux transfer into three parts to address this challenge, hence the three-phase method[1]. With the three-phase method, the flux transfer from the sky to indoor points was divided into three parts: 1) sky to the outer window surface, 2) the outer window surface to the inner window surface (i.e., a BSDF) and 3) inner window surface to indoor points. Shading systems represented by BSDF can now be swapped easily to enable parametric analysis.

3.1.5 BSDF for solar heat gain calculations

The ability of a fenestration system to manage solar heat gains is represented by its Directional Solar Heat Gain Coefficient (DSHGC) or angle-dependent g-value[2], which is a measure of the total fraction of incident solar irradiance that is transmitted into the building through a fenestration system for different incoming directions. The DSHGC of geometrically complex fenestration systems can be determined in the laboratory by applying a calorimetric measurement method[3]. Such measurements are important for verification of DSHGC that are calculated analytically or through BSDF-based workflows.

The DSHGC has two components: 1) the optically transmitted solar irradiance, and 2) the fraction of solar radiation which is absorbed in the system and then released by convection and radiation to the indoor environment.

The solar irradiance that is optically transmitted through a scattering fenestration system can be effectively represented by a broadband BSDF covering the entire solar spectral range or by BSDFs for a selection of narrower bands (see Section 3.4.4.5). The spatial resolution of BSDF datasets for building energy analysis can be kept low, e.g., the Klems BSDF format is used in EnergyPlus. Calculation of transmitted solar irradiance based on a BSDF representation of fenestration systems allows the calculation of the shortwave radiative energy that is absorbed by each indoor surface. In cases where indoor surfaces have very different thermal mass (e.g., lightweight furniture versus massive walls and floors), the distribution of shortwave solar radiation in a room can have a noticeable impact on the calculation of indoor air temperatures and energy demands.

BSDF datasets for the solar spectral range are difficult to determine experimentally. Further investigation is still required to determine whether broadband signals (e.g., with InGaAs detectors) are

[1] Ward, G., Mistrick, R., Lee, E.S., McNeil, A. Jonsson, J., 2011. Simulating the Daylight Performance of Complex Fenestration Systems Using Bidirectional Scattering Distribution Functions within Radiance. Leukos 7 (4): 241-261.
[2] Bueno, B, Cejudo-Lopez, J.M., Kuhn, T.E., 2017. A general method to evaluate the thermal impact of complex fenestration systems in building zones. Energy and Buildings 155: 43–53. https://doi.org/10.1016/j.enbuild.2017.08.055
[3] Kuhn, T.E. "Calorimetric determination of the solar heat gain coefficient g with steady-state laboratory measurements", Energy and Buildings 84 (2014)388–402, http://dx.doi.org/10.1016/j.enbuild.2014.08.021

suitable for experimentally deriving a BSDF in the near infrared (NIR) spectral range. For many shading devices, however, the assumption of a spectrally flat behavior can be made, e.g. often (but not always) for “neutral” white, grey or black devices. In those cases, BSDF datasets determined with silicon diode detectors can be used for building energy analysis as well. It must be noted that the reflection component of the BSDF dataset of a shading device is also important in determining the solar-control function of the device and thus must be paid the same attention as the transmission component.

In order to obtain the BSDF for the solar spectral range of a fenestration system as required by building energy simulation programs such as EnergyPlus, the BSDF dataset of the shading device must be combined with the BSDF of a glazing unit. Tools such as LBNL’s WINDOW software offer the Klems method[1] for this purpose. LBNL’s WINDOW software can be applied to generate a Klems BSDF of a glazing unit and a shading device for the solar spectral range from the individual spectrally resolved and broadband BSDF datasets of the glazing unit and the shading device, respectively (see Section 3.4.4.5). Spectrally resolved BSDF datasets of non-scattering and isotropic components such as glass panes are determined analytically by LBNL’s WINDOW from the normal-hemispherical transmittance and reflectance, and from coating information of the glass pane. The calculation of the BSDF of a fenestration system from the BSDF of its individual component layers generates the angle-resolved absorptance of each component as a by-product. This information is then used by the building energy simulation tool to solve an energy balance at each surface of the multilayer fenestration system[2], which determines its temperature distribution and the second term of the DSHGC. In doing so, the gas properties of the gaps between the glazing and shading layers are explicitly taken into account.

3.1.6 BSDF for glare risk assessment

More and more standards and certification systems are including daylighting in their criteria, where glare caused by daylight is an essential part. The European Standard EN 17017[3], for example, requires that the DGP not exceed a maximum value (0.35, 0.40, or 0.45, depending on the level of recommendation) for more than 5 % of the usage time of the space. This in turn implies that the architect or lighting designer has the appropriate simulation software available to perform these annual calculations. Since a building is always developed over numerous variants to the final design, software is needed that can perform such evaluations quickly and reliably.

For glare risk assessments, sunlight, whether transmitted, scattered, or reflected, needs to be predicted at highest accuracy due to its high intensity, especially for systems that allow specular transmission or reflection, e.g., for fabrics with openness, blinds, or (mirror) louvers. If available, proxy geometry can be used for the direct component simulation in the shadow testing algorithm.

[1] Klems, J.H., 1994a. A new method for predicting the solar heat gain of complex fenestration systems: I. Overview and derivation of the matrix layer calculation. ASHRAE Transactions 100 (1): 1065-1072.
[2] ISO 15099. Thermal performance of windows, doors and shading devices. Detailed calculations; 2003.
[3] EN 17037:2018. Daylight in Buildings.

Unfortunately, this is not always possible, either because the geometry is not available (e.g., for fabrics) or prohibited by the manufacturer because of intellectual property protection.

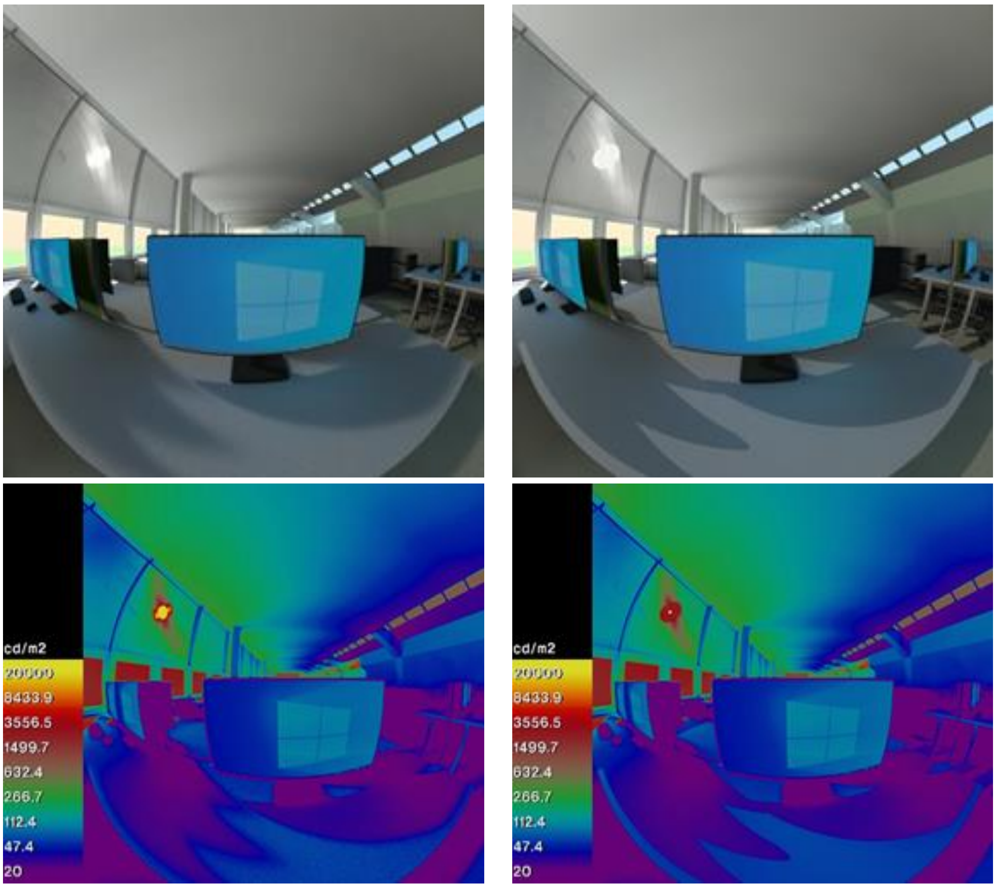
In these cases, tabular BSDFs are needed. Low-resolution BSDF lumps light peaks into large solid angles, which makes it unsuitable for glare metrics including contrast terms, i.e., luminance-based evaluations, such as DGP or DGI. High-resolution BSDF and the five-phase method[1] partially solved this problem by calculating the diffuse component separately from the direct sun component. Still, impracticably high resolutions of BSDF are required to capture peak luminance values caused by the sun as seen through forward scattering and specular transmitting materials. To overcome this limitation, Geisler-Moroder et al.[2*] developed a peak extraction (PE) algorithm, which separates the transmission peaks, associated with the view-through component of the transmission, from the rest of the BSDF dataset (Figure 5).

Sepulveda et al.[3*] benchmark BSDF methods for glare risk assessments in terms of accuracy and computational speed. Two different approaches are investigated:

- directly in the ray-tracing process as a material description, and
- in matrix form through the five-phase method.

This study investigates the influence of Radiance parameters and complex fenestration system models on glare assessment. The choice of suitable Radiance parameters, depending on the daylight calculation method, is crucial to ensure suitable accuracy and low CPU time for annual glare calculations. A criterion based on computational time was proposed for the selection of the fastest daylight calculation method for annual glare analysis. Different sampling strategies based on semi-annual periods and sun visibility were evaluated in terms of annual glare protection performance and computational time. The findings of this paper can help architects and practitioners to set up parameters and calculation methods for efficient annual glare calculations. In addition, Bueno et al.[4*] propose a simplified workflow for glare risk assessment based on low-resolution BSDF combined with Radiance's peak extraction algorithm.

[1] McNeil, Andrew. The Five-Phase Method for Simulating Complex Fenestration with Radiance. Radiance on-line tutorial, 2013, https://www.radiance-online.org/learning/tutorials/fivephasetutorialfiles/Tutorial-FivePhaseMethod_v2.pdf
[2*] Geisler-Moroder, D., Ward, G.J., Wang, T., Lee, E.S., 2021. Peak extraction in daylight simulations using BSDF data. Proceedings of Building Simulation 2021, International Building Performance Simulation Association, Bruges, September 1-3, 2021.
[3*] Sepúlveda, A., Bueno B., Wang T., Wilson H.R.. Benchmark of methods for annual glare risk assessment. Building and environment 201 (2021), ISSN: 0360-1323. DOI: 10.1016/j.buildenv.2021.108006
[4*] Bueno B., Sepúlveda A., Maurer C., Wacker S., Wang T., Kuhn T.E., Wilson H.R.. Easy-to-Implement Simulation Strategies for Annual Glare Risk Assessments based on the European Daylighting Standard EN 17037. Proceedings of Building Simulation 2021, International Building Performance Simulation Association, Bruges, September 1-3, 2021.



Without PE With PE

Figure 5 Upper row: Point-in-time rendering. Lower row: False-color luminance maps. Simulationw without (left) and with (right) peak extraction from the high-resolution BSDF data (max. 4096x4096). Note the differences in the sharpness of the shadow patterns and the size and luminance of the sun patch. The maximum luminance is 163K cd/m^2 (left) and 4.26M cd/m^2 (right). Source: Ward et al. (2021)[1*].

[1*] Ward G.J., Bueno B., Geisler-Moroder D., Grobe L.O., Jonsson J.C., Lee E.S., Wang T., Wilson H.R. Daylight Simulation Workflows Incorporating Measured Bidirectional Scattering Distribution Functions. Energy and Buildings 259 (2022) 111890 https://doi.org/10.1016/j.enbuild.2022.111890

3.1.7 Parametric study of energy performance for a range of shading products

Generic window attachments (theoretical ranges of performance):

The energy performance of window attachments (window shading, surface-applied films, and secondary window systems), mounted both indoors and outdoors, was modeled for a large number of window combinations with window attachments in typical residential buildings and in varied climates throughout the United States. The WINDOW software tool (LBNL 2013) was utilized to calculate component energy performance indices (U, SHGC, Tvis) and the EnergyPlus[1] software tool was utilized to calculate whole-building energy performance for a range of climates.

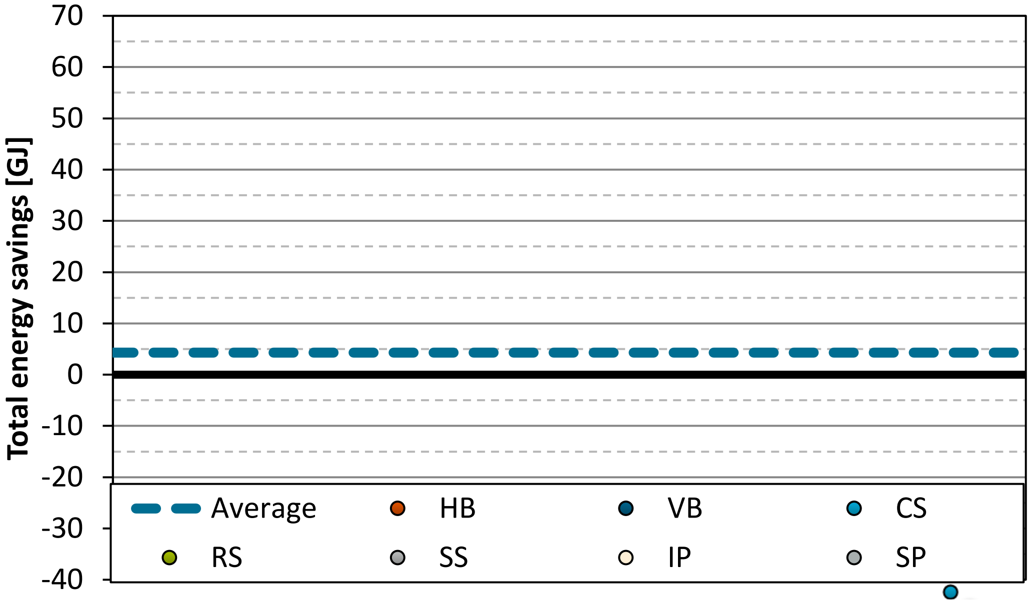
Based on an occupant behavioral study[2], typical operational (deployment) patterns were identified for three different regions in the country (North, Central, and South), for heating and cooling seasons, and the time of day (morning, afternoon, and evening/night). These schedules were then used to weight energy use for the three simulated deployment scenarios (shading open, half open, and closed) on an annual basis. The study provides a comprehensive examination of a wide range of interior and exterior systems and covers a large theoretical range of optical and thermal parameters (e.g., conductivity, emissivity, Tsol, Rsol). While many products on the market have a more limited range of parameters, this study shows the technical potential that can be achieved if technical development allows it.

Energy savings from window attachments can be substantial, as Figure 6 shows. However, the energy study also shows mixed savings results in northern and central U.S. climates (heating-dominated and mixed climates), due to variable insulating properties and the role of some systems in admitting or blocking solar gain. In cooling-dominated climates, where solar control is very important, all window attachments save energy. This is due to their universal lowering of the Solar Heat Gain Coefficient (SHGC), which reduces solar gains in the building and thus reduces cooling energy use. Exterior (outdoor-mounted) attachments are generally more effective in saving cooling energy, but that does not always translate to the highest overall energy savings due to a potential increase (penalty) in heating energy. While manual operation of window shading can have mixed results in heating-dominated and mixed climates, automation of these shading systems can maximize energy savings in those climates as well. Limited studies[3] show potential for increased energy savings when shading systems are automated.

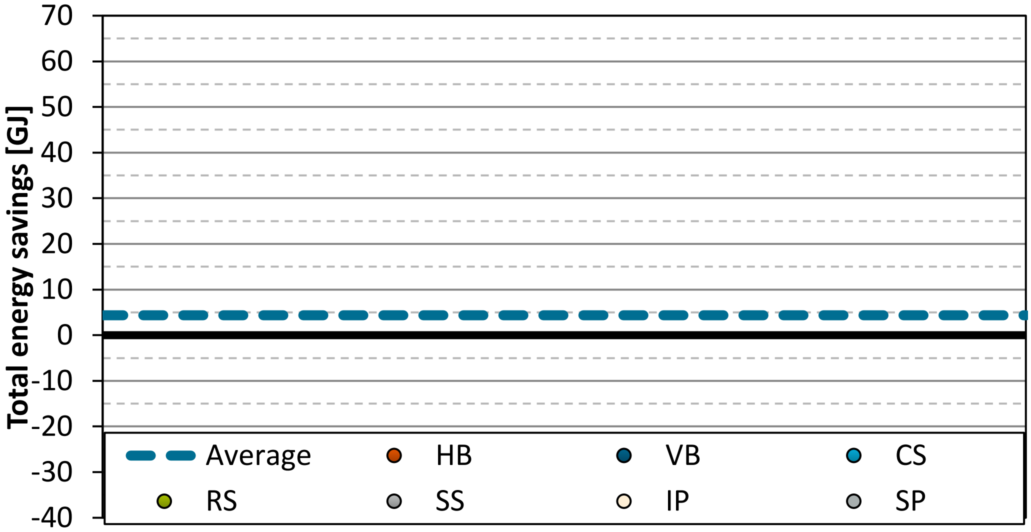
A summary of results is shown in the following two figures, one for a typical heating climate and the other for a typical cooling climate, where the house type for the heating climate was a two-story house with a basement, applying gas heating and electric air conditioning. For the cooling climate,

[1] DOE. EnergyPlus version 8.0. U.S. Department of Energy, Energy Efficiency and Renewable Energy (DOE), Office of Building Technologies. 2013. www.energyplus.gov
[2] Bickel, S., Phan-Gruber, E., Christie, S., DRI. “Residential Windows and Window Coverings: A Detailed View of the Installed Base and User Behavior” D&R International, Ltd. Silver Spring, MD. February 2013
[3] Firlag, S., Yazdanian, M., Curcija, D.C., Kohler, C., Vidanovic, S., Hart, R., Czarnecki, S. “Control algorithms for dynamic windows for residential buildings”, Energy and Buildings, 109, (2015), 157-173. https://doi.org/10.1016/j.enbuild.2015.09.069

the example taken was a two-story house with a slab-on-grade construction, applying a heat pump system for heating and cooling.



(a)



(b)

HB	Horizontal Louvered Blind	IP	Interior Window Panel
VB	Vertical Louvered Blind	SP	Storm Panel
CS	Cellular Shade	IF	Interior Applied Film
RS	Roller Shade	EF	Exterior Applied Film
SS	Solar Screen	AF	Fixed Awning
		AD	Drop-arm Awning

Figure 6 Average energy savings for different window attachment types installed over the baseline windows for (a) a two-story house with a basement, applying gas heating and electric air conditioning in a heating-dominated climate; (b) a two-story house with a slab-on-grade construction and applying a heat pump system for heating and cooling in a cooling-dominated climate. Each data point represents the result for one specific window attachment product of the type indicated by its color.

Energy performance of actual products:

A range of window attachment products using actual product data was modeled both as stand-alone components installed over the baseline windows, resulting in indices of energy performance (U, SHGC, Tvis) and installed over baseline windows in a typical house, resulting in energy performance indices, EP_C and EP_H , which are the main energy performance rating indices for AERC rating and certification[1]. These indices are non-dimensional, ranging from 0 to 100, where 0 means that a window attachment product does not have any energy effect on the baseline window performance and 100 means that the window attachment makes the window system net energy zero. Figure 9 to Figure 20 below show the distribution performance indices for a range of different window attachment products.

Type	No.	Name / Description	ε_f -	ε_b -	Tir -	O -	TvisF -	RvisF -	TsolF -	RsolF -	Side gaps mm	Top/Bot gaps mm	U $W/m^2 \cdot K$	SHGC -	VT -	AL l/s	EPc	EPh
Cellular Shade (CS)	1	Single cell. Light color. (Levolor) - CS03	0.806	0.806	0.008	0.000	0.228	0.660	0.220	0.630	3.000	0.000	1.615	0.264	0.174	0.944	38	7
	2	Stacked double cell. Light color.(Levolor) - CS04	0.790	0.790	0.000	0.000	0.061	0.679	0.058	0.651	3.000	0.000	1.494	0.214	0.046	0.944	43	8
	3	Cell-in-cell. Light color (HD) - CS07	0.875	0.875	0.000	0.009	0.041	0.545	0.041	0.504	3.000	0.000	1.573	0.271	0.029	0.944	37	11
	4	Single cell. Blackout, low-e. (HD) - CS10	0.905	0.905	0.000	0.000	0.000	0.591	0.000	0.579	3.000	0.000	1.584	0.253	0.000	0.944	39	8
	5	Single cell. Light Color, Sheer (HD) - CS11	0.668	0.668	0.203	0.590	0.564	0.387	0.566	0.380	3.000	0.000	2.172	0.442	0.420	0.944	19	5
	6	Single cell. Light color. no side gaps (Levolor) - CS03	0.806	0.806	0.008	0.000	0.228	0.660	0.220	0.630	0.000	0.000	1.427	0.253	0.174	0.944	39	10
	7	Stacked double cell. Light color. no side gap (Levolor) - CS04	0.790	0.790	0.000	0.000	0.061	0.679	0.058	0.651	0.000	0.000	1.258	0.195	0.046	0.944	44	12
	8	Triple cell Blackout low-e (HD) (no side gap) Interior::CS::BW01	0.881	0.881	0.000	0.000	0.000	0.555	0.000	0.515	0.000	0.000	1.063	0.207	0.000	0.944	42	21

Figure 7 Energy Performance Indices of Cellular Shades.

Type	No.	Name / Description	ε_f -	ε_b -	Tir -	O -	TvisF -	RvisF -	TsolF -	RsolF -	Side gaps mm	Top/Bot gaps mm	U $W/m^2 \cdot K$	SHGC -	VT -	AL l/s	EPc	EPh
Solar Screens (SS)	24	Light colored, low openness, Indoor. Alkenz-Sunshadow 3000 NET 1% N001	0.895	0.895	0.033	0.033	0.124	0.845	0.175	0.740	3.000	0.000	1.976	0.192	0.098	0.944	67	-29
	25	Dark colored, low openness, Indoor Alkenz Sunshadow - 3000 NET 1% N901	0.866	0.866	0.058	0.000	0.000	0.044	0.000	0.044	3.000	0.000	1.976	0.487	0.000	0.944	17	20
	26	Light colored, High openness, Indoor. Alkenz-Sunshadow 3000 NET 5% N001	0.831	0.831	0.088	0.088	0.197	0.780	0.249	0.680	3.000	0.000	2.046	0.235	0.155	0.944	61	-26
	27	Dark colored, High openness, Indoor. Alkenz-Sunshadow 3000 NET 5% N901	0.848	0.848	0.066	0.066	0.054	0.048	0.055	0.047	3.000	0.000	2.020	0.500	0.037	0.944	16	19
	28	Light colored (room facing) low-e (outdoor facing), 4% openness,	0.272	0.786	0.057	0.057	0.072	0.678	0.075	0.694	3.000	0.000	1.780	0.240	0.055	0.944	60	-5
	29	Light colored, low openness, Outdoor. Alkenz-Sunshadow 3000 NET 1% N001	0.895	0.895	0.033	0.033	0.124	0.845	0.175	0.740	3.000	0.000	1.876	0.109	0.094	0.944	80	-40
	30	Dark colored, low openness, Outdoor. Sunshadow - 3000 NET 1% N901	0.866	0.866	0.058	0.000	0.000	0.044	0.000	0.044	3.000	0.000	1.869	0.085	0.000	0.944	79	-40
	31	Light colored, High openness, Outdoor.	0.831	0.831	0.088	0.088	0.197	0.780	0.249	0.680	3.000	0.000	1.893	0.160	0.148	0.944	73	-32
	32	Dark colored, High openness, Outdoor.	0.848	0.848	0.066	0.066	0.054	0.048	0.055	0.047	3.000	0.000	1.886	0.112	0.037	0.944	76	-38
	33	Light colored, low openness, Indoor, sealed.	0.895	0.895	0.033	0.033	0.124	0.845	0.175	0.740	0.000	0.000	1.976	0.198	0.098	0.944	67	-27
	34	Dark colored, low openness, Outdoor, sealed	0.866	0.866	0.058	0.000	0.000	0.044	0.000	0.044	0.000	0.000	1.976	0.090	0.000	0.944	79	-39

Figure 8 Energy Performance Indices of Roller Shades.

[1] Peng, J; **Curcija, D.C.**; and Hart, R.G. 2021. Energy Performance Indices EPC and EPH Calculation Methodology and Implementation in Software tool. LBNL Technical Report. Berkeley, CA. September 2021. https://windows.lbl.gov/sites/default/files/Downloads/EPC_and_EPH_Calculation_Methodology_2021-09-30.pdf

Type	No.	Name / Description	ε_f -	ε_b -	Tir -	O -	TvisF -	RvisF -	TsolF -	RsolF -	Side gaps mm	Top/Bot gaps mm	U $W/m^2 \cdot K$	SHGC -	VT -	AL l/s	EPc	EPh
Venetian Blind (VB)	9	Off White Venetian Blind 24 mm, 1.5 mm rise, indoor	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	3.000	0.000	N/A	N/A	N/A	N/A	36	-11
		Slat angle=0	0.900	0.900	0.000	N/A	0.000	0.743	0.000	0.677	3.000	0.000	2.291	0.615	0.639	0.944	N/A	N/A
		Slat angle=45	0.900	0.900	0.000	N/A	0.000	0.743	0.000	0.677	3.000	0.000	2.254	0.415	0.191	0.944	N/A	N/A
		Slat angle=-45	0.900	0.900	0.000	N/A	0.000	0.743	0.000	0.677	3.000	0.000	2.256	0.422	0.219	0.944	N/A	N/A
		Slat angle=?/Closed	0.900	0.900	0.000	N/A	0.000	0.743	0.000	0.677	3.000	0.000	2.288	0.260	0.010	0.944	N/A	N/A
	10	Dark Blue Venetian Blind 24 mm, 1.5 mm rise, indoor	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	3.000	0.000	N/A	N/A	N/A	N/A	12	7
		Slat angle=0	0.900	0.900	0.000	N/A	0.000	0.073	0.000	0.186	3.000	0.000	2.291	0.622	0.627	0.944	N/A	N/A
		Slat angle=45	0.900	0.900	0.000	N/A	0.000	0.073	0.000	0.186	3.000	0.000	2.254	0.519	0.077	0.944	N/A	N/A
		Slat angle=-45	0.900	0.900	0.000	N/A	0.000	0.073	0.000	0.186	3.000	0.000	2.256	0.522	0.078	0.944	N/A	N/A
		Slat angle=?/Closed	0.900	0.900	0.000	N/A	0.000	0.073	0.000	0.186	3.000	0.000	2.288	0.479	0.000	0.944	N/A	N/A
	11	White Venetian Blind 2", PVC, Flat, 5 mm thick, indoor	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	3.000	0.000	N/A	N/A	N/A	N/A	42	-11
		Slat angle=0	0.733	0.733	0.000	N/A	0.000	0.829	0.003	0.814	3.000	0.000	2.253	0.631	0.678	0.944	N/A	N/A
		Slat angle=45	0.733	0.733	0.000	N/A	0.000	0.829	0.003	0.814	3.000	0.000	2.203	0.399	0.268	0.944	N/A	N/A
		Slat angle=-45	0.733	0.733	0.000	N/A	0.000	0.829	0.003	0.814	3.000	0.000	2.203	0.399	0.268	0.944	N/A	N/A
		Slat angle=84/Closed	0.733	0.733	0.000	N/A	0.000	0.829	0.003	0.814	3.000	0.000	2.123	0.214	0.031	0.944	N/A	N/A
	12	Wood Venetian Blind 2", Flat, 3.2 mm thick, indoor	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	3.000	0.000	N/A	N/A	N/A	N/A	15	8
		Slat angle=0	0.866	0.866	0.058	N/A	0.000	0.133	0.001	0.234	3.000	1.000	2.253	0.631	0.678	0.944	N/A	N/A
		Slat angle=45	0.866	0.866	0.058	N/A	0.000	0.133	0.001	0.234	3.000	0.000	2.228	0.519	0.132	0.944	N/A	N/A
		Slat angle=-45	0.866	0.866	0.058	N/A	0.000	0.133	0.001	0.234	3.000	0.000	2.228	0.519	0.132	0.944	N/A	N/A
		Slat angle=84/Closed	0.866	0.866	0.058	N/A	0.000	0.133	0.001	0.234	3.000	0.000	2.203	0.459	0.002	0.944	N/A	N/A

Figure 9 Energy Performance Indices of Horizontal Louvered Blinds (Venetian Blinds).

Type	No.	Name / Description	ε_f -	ε_b -	Tir -	O -	TvisF -	RvisF -	TsolF -	RsolF -	Side gaps mm	Top/Bot gaps mm	U $W/m^2 \cdot K$	SHGC -	VT -	AL l/s	EPc	EPh
Solar Screens (SS)	24	Light colored, low openness, Indoor. Alkenz-Sunshadow 3000 NET 1% N001	0.895	0.895	0.033	0.033	0.124	0.845	0.175	0.740	3.000	0.000	1.976	0.192	0.098	0.944	67	-29
	25	Dark colored, low openness, Indoor Alkenz Sunshadow - 3000 NET 1% N901	0.866	0.866	0.058	0.000	0.000	0.044	0.000	0.044	3.000	0.000	1.976	0.487	0.000	0.944	17	20
	26	Light colored, High openness, Indoor. Alkenz-Sunshadow 3000 NET 5% N001	0.831	0.831	0.088	0.088	0.197	0.780	0.249	0.680	3.000	0.000	2.046	0.235	0.155	0.944	61	-26
	27	Dark colored, High openness, Indoor. Alkenz-Sunshadow 3000 NET 5% N901	0.848	0.848	0.066	0.066	0.054	0.048	0.055	0.047	3.000	0.000	2.020	0.500	0.037	0.944	16	19
	28	Light colored (room facing) low-e (outdoor facing), 4% openness,	0.272	0.786	0.057	0.057	0.072	0.678	0.075	0.694	3.000	0.000	1.780	0.240	0.055	0.944	60	-5
	29	Light colored, low openness, Outdoor. Alkenz-Sunshadow 3000 NET 1% N001	0.895	0.895	0.033	0.033	0.124	0.845	0.175	0.740	3.000	0.000	1.876	0.109	0.094	0.944	80	-40
	30	Dark colored, low openness, Outdoor. Sunshadow - 3000 NET 1% N901	0.866	0.866	0.058	0.000	0.000	0.044	0.000	0.044	3.000	0.000	1.869	0.085	0.000	0.944	79	-40
	31	Light colored, High openness, Outdoor.	0.831	0.831	0.088	0.088	0.197	0.780	0.249	0.680	3.000	0.000	1.893	0.160	0.148	0.944	73	-32
	32	Dark colored, High openness, Outdoor.	0.848	0.848	0.066	0.066	0.054	0.048	0.055	0.047	3.000	0.000	1.886	0.112	0.037	0.944	76	-38
	33	Light colored, low openness, Indoor, sealed.	0.895	0.895	0.033	0.033	0.124	0.845	0.175	0.740	0.000	0.000	1.976	0.198	0.098	0.944	67	-27
	34	Dark colored, low openness, Outdoor, sealed	0.866	0.866	0.058	0.000	0.000	0.044	0.000	0.044	0.000	0.000	1.976	0.090	0.000	0.944	79	-39

Figure 10 Energy Performance Indices of Solar Screens (non-operable).

Type	No.	Name / Description	ε_f -	ε_b -	Tir -	O -	TvisF -	RvisF -	TsolF -	RsolF -	Side gaps mm	Top/Bot gaps mm	U $W/m^2 \cdot K$	SHGC -	VT -	AL l/s	EPc	EPh
Window Panel (WP)	35	Clear Glass Window Panel Indoor::WP::I	0.840	0.840	0.000	N/A	0.899	0.083	0.834	0.075	N/A	N/A	1.698	0.571	0.616	0.189	12	84
	36	Low-e Glass Window Panel Indoor::WP::I	0.840	0.149	0.000	N/A	0.884	0.079	0.735	0.105	N/A	N/A	1.355	0.543	0.608	0.189	16	104
	37	Clear Glass Window Panel Outdoor::WP::O	0.840	0.840	0.000	N/A	0.899	0.083	0.834	0.075	N/A	N/A	1.745	0.576	0.620	0.236	14	80
	38	Low-e Glass Window Panel Outdoor::WP::O	0.840	0.149	0.000	N/A	0.884	0.079	0.735	0.105	N/A	N/A	1.434	0.525	0.608	0.236	18	95

Figure 11 Energy Performance Indices of Window Panels (non-operable).

Type	No.	Name / Description	ε_f -	ε_b -	Tir -	O -	TvisF -	RvisF -	TsolF -	RsolF -	Side gaps mm	Top/Bot gaps mm	U $W/m^2 \cdot K$	SHGC -	VT -	AL l/s	EPc	EPh
Applied Film (AF)	39	Absorbing Film, Indoor	0.881	0.840	0.000	N/A	0.320	0.068	0.380	0.078	N/A	N/A	2.618	0.522	0.242	0.944	14	-17
	40	Low-e Film, Indoor	0.840	0.048	0.000	N/A	0.343	0.432	0.211	0.485	N/A	N/A	1.868	0.257	0.267	0.944	52	-17
	41	Absorbing Film, Outdoor	0.881	0.840	0.000	N/A	0.320	0.068	0.380	0.078	N/A	N/A	2.592	0.360	0.242	0.944	43	-45
	42	Low-e Film, Outdoor	0.840	0.048	0.000	N/A	0.343	0.432	0.211	0.485	N/A	N/A	2.563	0.217	0.267	0.944	59	-57

Figure 12 Energy Performance Indices of Surface-Applied Films.

Type	No.	Name / Description	ε_f -	ε_b -	Tir -	O -	TvisF -	RvisF -	TsolF -	RsolF -	Side gaps mm	Top/Bot gaps mm	U $W/m^2 \cdot K$	SHGC -	VT -	AL l/s	EPc	EPh
Pleated Shade (PS)	43	Light colored Pleated Shade, Low Openness, Indoor	0.874	0.874	0.057	0.010	0.347	0.630	0.381	0.550	3.000	0.000	1.998	0.336	0.293	0.944	31	-2
	44	Light colored Pleated Shade, High Openness, Indoor	0.780	0.780	0.129	0.100	0.492	0.495	0.477	0.476	3.000	0.000	2.084	0.390	0.362	0.944	25	2

Figure 13 Energy Performance Indices of Pleated Shades.

Type	No.	Name / Description	ε_f -	ε_b -	Tir -	O -	TvisF -	RvisF -	TsolF -	RsolF -	Side gaps mm	Top/Bot gaps mm	U $W/m^2 \cdot K$	SHGC -	VT -	AL l/s	EPc	EPh
Vertical Louvered Blinds (VL)	45	Vertical slat - Snow	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	3.000	0.000	N/A	N/A	N/A	N/A	42	-19
		Slat angle=0	0.766	0.766	0.084	N.A.	0.000	0.866	0.029	0.831	3.000	0.000	2.243	0.600	0.628	0.944	N/A	N/A
		Slat angle=45	0.766	0.766	0.084	N.A.	0.000	0.866	0.029	0.831	3.000	0.000	2.212	0.383	0.253	0.944	N/A	N/A
		Slat angle=-45	0.766	0.766	0.084	N.A.	0.000	0.866	0.029	0.831	3.000	0.000	2.218	0.392	0.302	0.944	N/A	N/A
		Slat angle=84/Closed	0.766	0.766	0.084	N.A.	0.000	0.866	0.029	0.831	3.000	0.000	2.262	0.205	0.024	0.944	N/A	N/A
	46	Vertical slat - Mocha	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	3.000	0.000	N/A	N/A	N/A	N/A	23	-2
		Slat angle=0	0.825	0.825	0.046	N.A.	0.052	0.201	0.213	0.449	3.000	0.000	2.232	0.630	0.678	0.944	N/A	N/A
		Slat angle=45	0.825	0.825	0.046	N.A.	0.052	0.201	0.213	0.449	3.000	0.000	2.202	0.473	0.183	0.944	N/A	N/A
		Slat angle=-45	0.825	0.825	0.046	N.A.	0.052	0.201	0.213	0.449	3.000	0.000	2.202	0.473	0.183	0.944	N/A	N/A
		Slat angle=84/Closed	0.825	0.825	0.046	N.A.	0.052	0.201	0.213	0.449	3.000	0.000	2.271	0.386	0.037	0.944	N/A	N/A

Figure 14 Energy Performance Indices of Vertical Louvered Blinds.

Type	No.	Name / Description	ε_f -	ε_b -	Tir -	O -	TvisF -	RvisF -	TsolF -	RsolF -	Side gaps mm	Top/Bot gaps mm	U $W/m^2 \cdot K$	SHGC -	VT -	AL l/s	EPc	EPh
Roller Shutters (ER)	47	BronzeSingleWallSteel::ER::O	0.795	0.795	0.000	0.952	0.000		0.000		3.000	0.000	1.941	0.451	0.000	0.944	54	-21
	48	WhiteDoubleWallInsulatedAlul::ER::O	0.819	0.821	0.000	0.000	0.000		0.000		3.000	0.000	1.836	0.381	0.290	0.944	62	-25

Figure 15 Energy Performance Indices of Roller Shutters.

Type	No.	Name / Description	ε_f -	ε_b -	Tir -	O -	TvisF -	RvisF -	TsolF -	RsolF -	Side gaps mm	Top/Bot gaps mm	U $W/m^2 \cdot K$	SHGC -	VT -	AL l/s	EPc	EPh
Operable Window Quilts (RS)	49	Room Darkening Quilt Sidetrack Roller Shade Indoor::RS::I	0.900	0.900	0.000	0.000	0.000	0.045	0.000	0.044	3.000	0.000	1.676	0.452	0.000	0.944	15	17
	50	Light Filtering Quilt Roller Shade Indoor::RS::I	0.900	0.900	0.000	0.000	0.393	0.445	0.403	0.443	3.000	0.000	1.860	0.381	0.290	0.944	28	6

Figure 16 Energy Performance Indices of Operable Window Quilts.

Type	No.	Name / Description	ε_f -	ε_b -	Tir -	O -	TvisF -	RvisF -	TsolF -	RsolF -	Side gaps mm	Top/Bot gaps mm	U $W/m^2 \cdot K$	SHGC -	VT -	AL l/s	EPc	EPh
Fixed Window Quilts (SS)	51	Room Darkening Quilt Sidetrack Solar Shade Indoor::SS::I	0.900	0.900	0.000	0.000	0.000	0.045	0.000	0.044	3.000	0.000	1.744	0.060	0.000	0.944	21	28
	52	Light Filtering Quilt Solar Shade Indoor::SS::I	0.900	0.900	0.000	0.000	0.393	0.445	0.403	0.443	3.000	0.000	1.860	0.020	0.000	0.944	41	8

Figure 17 Energy Performance Indices of Fixed Window Quilts.

Type	No.	Name / Description	ε_f -	ε_b -	Tir -	O -	TvisF -	RvisF -	TsolF -	RsolF -	Side gaps mm	Top/Bot gaps mm	U $W/m^2 \cdot K$	SHGC -	VT -	AL l/s	EPc	EPh
Awnings Fixed (AY)	53	Awning 1A Fixed - Dark::AY1A	0.835	0.835	0.057	0	0.000	0.022	0.000	0.021	N/A	N/A	2.590	0.194	0.214	0.944	58	-68
	54	Awning 1A Fixed - Light::AY1A	0.790	0.790	0.000	0.001	0.207	0.684	0.210	0.676	N/A	N/A	2.590	0.194	0.214	0.944	58	-68
	55	Awning 1B Fixed - Dark::AY1B	0.835	0.835	0.057	0	0.000	0.022	0.000	0.021	N/A	N/A	2.590	0.260	0.172	0.944	38	-43
	56	Awning 1B Fixed - Light::AY1B	0.790	0.790	0.000	0.001	0.207	0.684	0.210	0.676	N/A	N/A	2.590	0.313	0.308	0.944	31	-34
	57	Awning 2A Fixed - Dark::AY2A	0.835	0.835	0.057	0	0.000	0.022	0.000	0.021	N/A	N/A	2.590	0.328	0.256	0.944	24	-24
	58	Awning 2A Fixed - Light::AY2A	0.790	0.790	0.000	0.001	0.207	0.684	0.210	0.676	N/A	N/A	2.590	0.417	0.331	0.944	15	-16
	59	Awning 2B Fixed - Dark::AY2B	0.835	0.835	0.057	0	0.000	0.022	0.000	0.021	N/A	N/A	2.590	0.379	0.325	0.944	16	-16
	60	Awning 2B Fixed - Light::AY2B	0.790	0.790	0.000	0.0013	0.207	0.684	0.210	0.676	N/A	N/A	2.590	0.489	0.382	0.944	10	-11

Figure 18 Energy Performance Indices of Fixed Awnings.

Type	No.	Name / Description	ε_f -	ε_b -	Tir -	O -	TvisF -	RvisF -	TsolF -	RsolF -	Side gaps mm	Top/Bot gaps mm	U $W/m^2 \cdot K$	SHGC -	VT -	AL l/s	EPc	EPh
Awnings Seasonally Fixed (AS)	61	Awning 1A Seasonal - Dark::AS1A	0.835	0.835	0.057	0	0.000	0.022	0.000	0.021	N/A	N/A	2.590	0.165	0.040	0.944	44	-21
	62	Awning 1B Seasonal - Dark::AS1B	0.790	0.790	0.000	0.001	0.207	0.684	0.210	0.676	N/A	N/A	2.590	0.262	0.172	0.944	40	-18
	63	Awning 1A Seasonal - Light::AS1A	0.835	0.835	0.057	0	0.000	0.022	0.000	0.021	N/A	N/A	2.590	0.308	0.214	0.944	25	-11
	64	Awning 1B Seasonal - Light::AS1B	0.790	0.790	0.000	0.001	0.207	0.684	0.210	0.676	N/A	N/A	2.590	0.387	0.308	0.944	20	-9
	65	Awning 2A Seasonal - Dark::AS2A	0.835	0.835	0.057	0	0.000	0.022	0.000	0.021	N/A	N/A	2.590	0.330	0.256	0.944	15	-6
	66	Awning 2A Seasonal - Light::AS2A	0.790	0.790	0.000	0.001	0.207	0.684	0.210	0.676	N/A	N/A	2.590	0.377	0.325	0.944	9	-4
	67	Awning 2B Seasonal - Dark::AS2B	0.835	0.835	0.057	0	0.000	0.022	0.000	0.021	N/A	N/A	2.590	0.474	0.331	0.944	10	-4
	68	Awning 2B Seasonal - Light::AS2B	0.790	0.790	0.000	0.0013	0.207	0.684	0.210	0.676	N/A	N/A	2.590	0.489	0.382	0.944	6	-3

Figure 19 Energy Performance Indices of Seasonally Adjusted Awnings.

Type	No.	Name / Description	ε_f -	ε_b -	Tir -	O -	TvisF -	RvisF -	TsolF -	RsolF -	Side gaps mm	Top/Bot gaps mm	U $W/m^2 \cdot K$	SHGC -	VT -	AL l/s	EPc	EPh
Awnings Operable (AO)	69	Awning 1A-1B Operable - Dark	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	27	-19
		Position 1A	0.835	0.835	0.057	0	0.000	0.022	0.000	0.021	N/A	N/A	2.590	0.165	0.040	0.944	N/A	N/A
		Position 1B	0.835	0.835	0.057	0	0.000	0.022	0.000	0.021	N/A	N/A	2.590	0.308	0.214	0.944	N/A	N/A
	70	Awning 1A-1B Operable - Light	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	22	-15
		Position 2A	0.790	0.790	0.000	0.001	0.207	0.684	0.210	0.676	N/A	N/A	2.590	0.262	0.172	0.944	N/A	N/A
		Position 2B	0.790	0.790	0.000	0.001	0.207	0.684	0.210	0.676	N/A	N/A	2.590	0.387	0.308	0.944	N/A	N/A
	71	Awning 2A-2B Operable - Dark	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	10	-7
		Position 1A	0.835	0.835	0.057	0	0.000	0.022	0.000	0.021	N/A	N/A	2.590	0.330	0.256	0.944	N/A	N/A
		Position 1B	0.835	0.835	0.057	0	0.000	0.022	0.000	0.021	N/A	N/A	2.590	0.474	0.331	0.944	N/A	N/A
	72	Awning 2A-2B Operable - Light	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	6	-4
		Position 2A	0.790	0.790	0.000	0.001	0.207	0.684	0.210	0.676	N/A	N/A	2.590	0.377	0.325	0.944	N/A	N/A
		Position 2B	0.790	0.790	0.000	0.0013	0.207	0.684	0.210	0.676	N/A	N/A	2.590	0.489	0.382	0.944	N/A	N/A

Figure 20 Energy Performance Indices of Operable Awnings.

3.1.8 Software developments within the ICON project

Several software tools were developed and/or updated during this project. Most of the tools are open source posted on GitHub and available to software developers. The tools range from calculation engines (WinCalc/PyWinCalc, Radiance/frads) to databases (metabase, IGSDB)

The WinCalc stand-alone calculation engine incorporates state-of-the-art calculation procedures for thermal and optical calculations of window and shading products, based on calculation procedures documented in ISO 15099, more recent developments for shading product calculations at LBNL and from the ICON project. The calculation engine calculations were completed and published as an open-source code on GitHub.This software tool contains documented API for third party developers to incorporate into their tools and GUIs. A python script was developed (PyWinCalc), which utilizes WinCalc API and allows users to run parametric simulations from the command line. Code for WinCalc and PyWinCalc is published as an open source and posted on GitHub (https://github.com/LBNL-ETA/Windows-CalcEngine)

One of the significant advances within the Radiance engine is the development and validation of the BSDF peak extraction algorithm. With tabular BSDF alone, such as those in Klems and tensor tree formats, the resolution is often not fine enough to resolve small sources, such as the sun. The consequence is that luminance is underestimated by orders of magnitude, depending on the BSDF resolution. The peak extraction algorithm was developed to evaluate the BSDF in and around the direction continuing the path of the non-deviated incident ray, determine whether there is a pronounced peak, and if so, model it as purely specular. (https://github.com/LBNL-ETA/Radiance) The frads Python library was developed to automate various Radiance simulation workflows, including support for a workflow involving high-resolution BSDF. (https://github.com/LBNL-ETA/frads)

The IGSDB database was developed as a cloud-based repository of glazing and shading products and the associated web tool, which allows users to upload data and view integrated properties. This database incorporates the new GraphQL API for the connection to the metabase. A web portal is available at: https://igsdb-icon.herokuapp.com. Another python-based script was developed for interface to the IGSDB and was posted at: https://github.com/LBNL-ETA/py_igsdb_optical_data.

The next generation of WINDOW and THERM tools (version 8) was initiated during the ICON project and an alpha version of these tools is posted at: https://windows.lbl.gov/therm-8-window-8. WINDOW8 uses the WinCalc engine and accesses the cloud-based IGSDB.

3.2 WP 2 - BIM-compatible virtual complex fenestration (CF) components and data base

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Results anticipated from WP2 in SoW: “A cloud-based, BIM-compatible, internationally recognized data base for architectural glazing, daylighting, solar-shading and active-solar (i.e. building-integrated PV and solar-thermal) components, combining the features of the International Glazing Data Base IGDB, the Complex Glazing Data Base CGDB and the new international virtual component data base for BIM usage will have been established. All data formats and specifications will be “open”. Internationally accessible semantics and structures will have been created within BIM (building information modelling) frameworks to accurately transfer relevant characteristics of glazing and solar-shading components through all stages of the building process – from component design through planning and construction to operation.”

3.2.1 Motivation

Architects, planners and engineers currently face several barriers when dealing with data about building envelopes. Sometimes, it's difficult to find the data they need. Sometimes, they find the data, but not in the format which their software application requires. Often, data sheets are available as a PDF file, requiring planners to type the data manually into their software application.

Manufacturers of building envelope components face barriers, too. They receive various product data for example from laboratories. They need to submit product data for example to databases of associations. Software manufacturers are asking for data and sometimes planners ask for specific data. Many different formats are being used and all files and versions need to be maintained properly.

There are several databases worldwide, for example the International Glazing Database (IGDB), the Complex Glazing Database (CGDB), the International Glazing and Shading Database (IGSDB) in North America and the European Solar Shading Database (ES-SDA) in Europe. It is a challenge for manufacturers to submit data about their products to several databases. For solar-active building envelope components, detailed optical, calorimetric and photovoltaic was not available in databases at the beginning of ICON.

To overcome these barriers, a vision was developed that the favorite building modeling software applications of practitioners and planners should be able to directly access the product data as a data set complying with a specific data schema, so that no manual steps are needed from planners or component manufacturers, and the data sets are available for various levels of detail. The aim is that planners can develop high-quality energy-efficient buildings faster and easier, benefiting from access to the vast database of products. For component manufacturers, it should be easy to store or submit the product data just once with many software applications using/accessing this data.

This vision is much larger than one work package in one research project. Therefore, collaborations were used as much as possible for example with the European Solar-Shading Organisation (ES-SO), but also with national research projects. Figure 21 presents a schematic drawing of the resulting concept. Like most people, planners are familiar with software applications with a graphical user interface. Usually, only software developers are familiar with the data exchange between a software application and servers with databases, which occurs via the GraphQL API.

In order to find the right data set, a software application typically sends a request to the application programming interface (API) of the metabase server. The metabase then forwards the request to all product databases, merges their responses and returns them to the software application.

When the software application knows the location of the required data set, it can download the data set directly from the product databases. In this way, the software application interacts with the databases automatically until a decision from the planner is needed.

The metabase manages unique identifiers for components and institutions. The unique identifier makes it possible to search for all data about a component in all databases of the network with one request to the metabase.

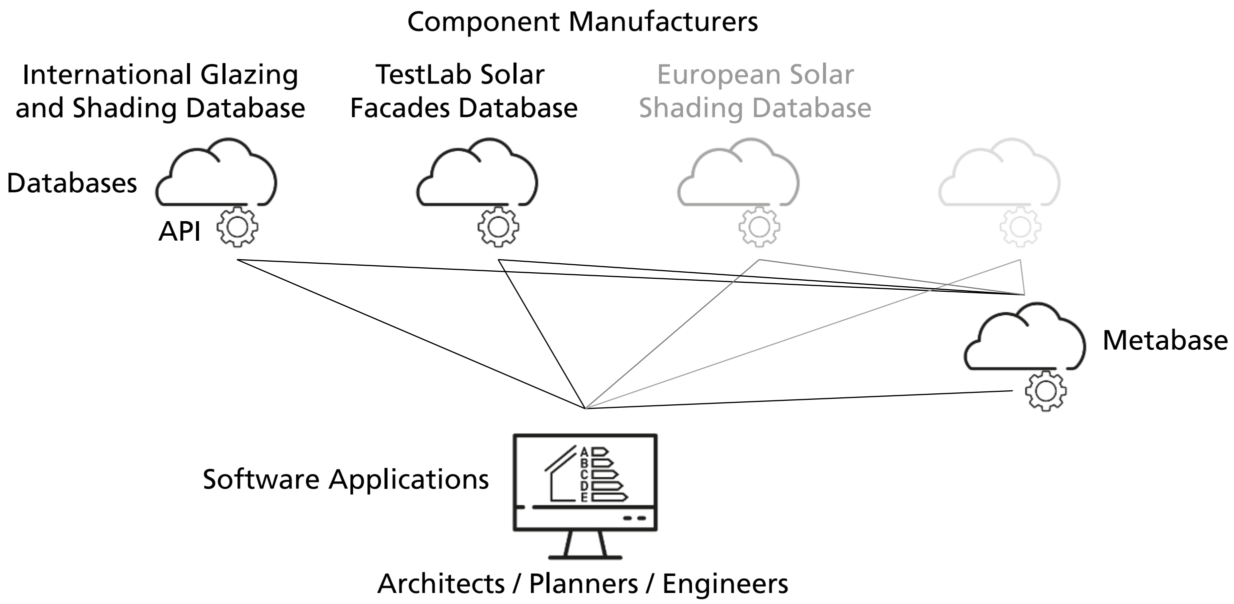


Figure 21 Schematic drawing of the network of product databases. Planners use software applications which directly access the product databases which are represented by clouds in the top row. A common application programming interface (API) facilitates this exchange and is represented by a gear wheel. A metabase manages the identifiers of components and institutions and can be used to query all databases at once.

It was a challenge that there was no data schema which could cover all optical data of building envelopes. There had been many formats for certain aspects of subsets of optical data with their own advantages and disadvantages. It is important for automated exchange of data that the request to servers and the answers of servers are specified well and can be validated automatically. Therefore, a data schema for optical data sets was developed and posted open-source on GitHub.

The large vision includes that software applications could make it in the long-term easy for planners to perform complex tasks without requiring them to understand all details of the process and of the complex data sets involved. Because of the large vision, this work package focused on the data schema for optical data sets and the integration of the International Glazing and Shading Databases (IGSDB) and of the European Solar Shading Database (ES-SDA) in the network of databases. The German research project SCOPE[1] provided the implementation of the metabase and a database for the TestLab Solar Facades of Fraunhofer ISE.

The concept allows the verification of identities and granting appropriate rights. The API specification enables interoperability between heterogeneous web servers. The software is portable so that databases can implemented on many operating systems. Data exchange is secured with HTTPS certificates. In the future, data sets could be approved with a digital signature. WP2 is therefore in

[1] https://www.projekt-scope.de

line with the requirements of the European project GAIA-X[1]. GAIA-X can therefore be an interesting option for future extensions of the network of product databases.

3.2.2 Data schema for optical data sets

The data schema for optical data sets has been developed as part of the API specification https://github.com/building-envelope-data/api It has been published as an open source and posted on GitHub. The specification wants to make it easy for component manufacturers and their associations to add such an API to their existing databases. At the same time, it shall make it easy for software companies to use the API. The structure of the API specification was broadly discussed within the ICON team and beyond. It should have only few breaking changes in the future. Figure 22 presents an optical data set as an example. All relevant details can be defined.

```json
{
  "data": [
    {
      "dataPoints": [
        {
          "incidence": {
            "direction": {
              "polar": 0
            },
            "wavelengths": {
              "integral": "visible"
            }
          },
          "emergence": {
            "direction": "hemispherical"
          },
          "results": {
            "transmittance": 0.63
          }
        }
      ]
    }
  ]
}
```

Figure 22	Example of an optical data set. The incident and emergent radiation and the results can be defined precisely.

The data schema is documented in a way that software developers can easily understand it. Therefore, all keys have a description as presented in Figure 23 for the key “polar”.

[1] https://www.data-infrastructure.eu

```
"properties": {
  "polar": {
    "$ref": "number.json#/$defs/degreeBetweenZeroAndNinetyWithUncertainty",
    "description": "The polar angle is the angle between the direction of incidence and an
    axis which is perpendicular to the surface of the sample. It can have values between 0°
    and 90°. A polar angle of 0° means that the direction of incidence is perpendicular to
    the sample. A polar angle of 90° means that the direction of incidence is parallel to
    the sample. If the sample has `azimuthalAngleInvariance`, then the optical results
    depend only on the polar angle and not on the azimuth angle. If the sample has a
    `profileAngle` symmetry whose direction is equal to the prime direction, then the
    profile angle can be calculated from the polar and azimuth angles."
  },
```

Figure 23 Description of the key “polar” and its allowed values.

Software developers need to be able to use the data easily. Therefore, JSON was chosen as the most widely used format for data exchange between web servers. High-quality open-source software packages are available which make it easy to parse JSON data and to process it in many programming languages. A JSON Schema like https://github.com/building-envelope-data/api/blob/develop/schemas/opticalData.json can be used to validate an optical data set automatically whether it fulfills all requirements of the schema. This helps to identify errors before they lead e.g. to a run-time error in a software application.

Bidirectional Scattering Distribution Function (BSDF) data can be formatted according to opticalData.json, too. Especially for format conversions, it is helpful to have such a general format covering the whole range of optical data sets. For practical reasons, additional formats are made available within the network of databases such as Klems and Tensor Tree. They provide a smaller size of the BSDF optical data set and can be used directly by the software Radiance.

3.2.3 International Glazing and Shading Database

The API implementation of the International Glazing and Shading Database (IGSDB) was developed and tested in this work package. It is now available at https://igsdb-icon.herokuapp.com/icon_graphql/ . Software companies can directly use this API or send queries to the API of the metabase https://www.buildingenvelopedata.org/graphql/ . The metabase then forwards the query to all databases, collects all answers, merges them and returns them in its response. Such interaction is familiar to software developers, but not to most people. Therefore, the websites https://igsdb-icon.herokuapp.com and https://www.buildingenvelopedata.org have been developed for the IGSDB and the metabase as a graphical user interface.

Figure 24 presents the almost 7000 components from IGSDB registered at buildingenvelopedata.org. The website can be used to query for optical data sets about these components. The website is fully based on the API. A search for all resources about one component is therefore translated into a query to the API as presented by

Figure 25. The API also enables searches for data sets which have for example the near-normal-hemispherical visible transmittance, the near-normal-hemispherical solar transmittance and the infrared emissivity within certain ranges.

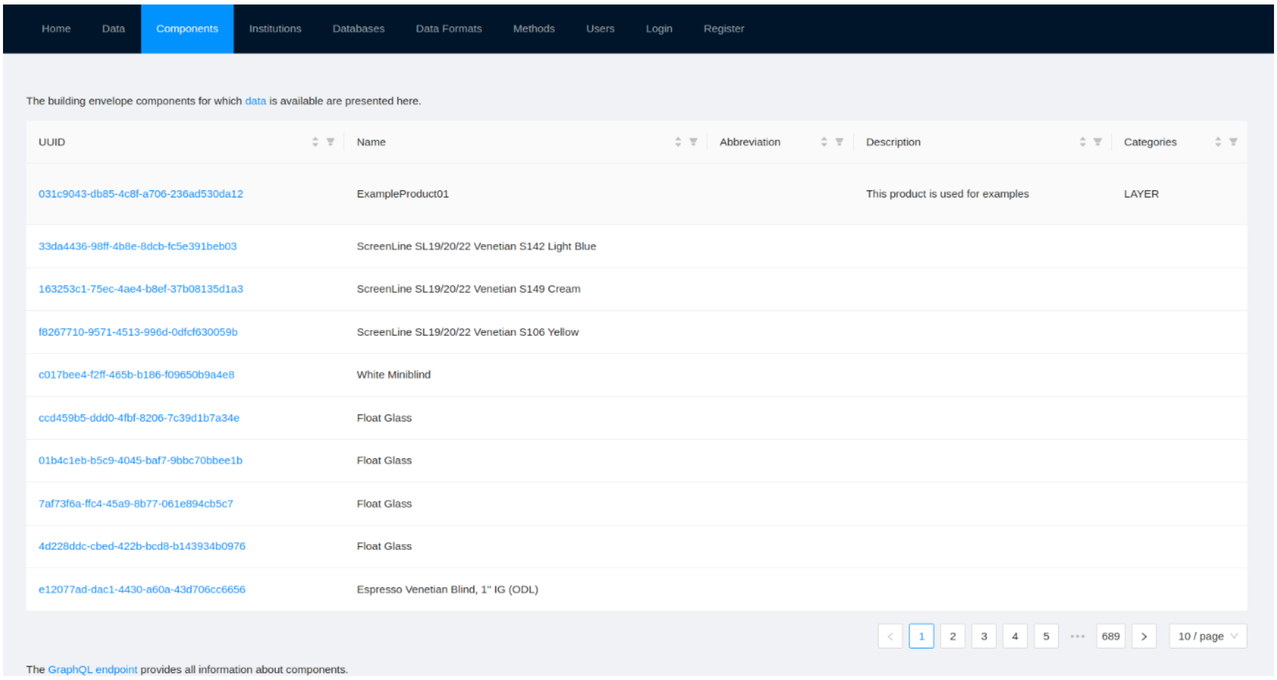


Figure 24 Screenshot of buildingenvelopedata.org with almost 7000 components registered from IGSDB.

Figure 25 Query to the Metabase for all resources about one component (left) with response from IGSDB (right).

3.2.4 European Solar Shading Database

The European Solar Shading Organisation (ES-SO) manages the European Solar Shading Database (ES-SDA)[1]. It offers product data about shading as HTML, text and PDF files. There has been a long and fruitful exchange with the ICON industry experts from ES-SO about optical data and data schemas. ES-SO has decided to implement the API specification with the opticalData.json so that software applications can directly ask ES-SDA for data. The network of product databases can be extended so that databases can choose which data they return to which user.

ES-SO has many tasks with high priority. Depending on the existing database, some resources are needed to implement the API specification with high performance and low maintenance costs. ES-SDA is therefore not yet integrated into the network of product databases. As soon as the API fulfills the specification, it will be connected to the network. Its product data can then be queried in the same ways as presented for the IGSDB.

3.2.5 TestLab Solar Facades Database

Within the project SCOPE, a database was created for the TestLab Solar Facades of Fraunhofer ISE as an example that laboratories can add additional measurement data when required. This database can be used to upload data beyond the scope of the IGSDB and to demonstrate possible future use of the network of databases. As the source code is available at https://github.com/building-envelope-data/database , new database can easily be created and added to the network.

3.3 WP 3 - Fraunhofer ISE as a European Regional Data Aggregator (RDA)

Contributors from Fraunhofer ISE: Helen Rose Wilson (WP leader), Adrienne Dietzmann, Johannes Hanek

Contributors from LBNL: Charlie Curcija (WP leader), Jacob Jonsson, Robin Mitchell

Results anticipated from WP3 in SoW: “Fraunhofer ISE will have been established as the regional data aggregator RDA for Europe to review, collect, manage and support European manufacturers who intend to contribute glazing and shading component data to the new internationally recognized data base. Joint strategies for the population of the new database with manufacturer data sets certified by independent labs will have been implemented.”

3.3.1 RDA concept

In order to streamline the submission and management of data for the International Glazing Data Base (IGDB) and the International Glazing and Shading Data Base (IGSDB) from international sources, LBNL proposed a framework for regional data aggregators (RDA) who are responsible for

[1] https://www.es-so-database.com/index.php/database

direct interaction with submitting companies in their own region (continent) during the data submission process.

The functional RDA process is depicted in a diagram shown in Figure 26, taking the web-based procedure for the IGSDB as an example. This process includes data submission, checking, peer review, potential re-submission in the cases where data was not correct, data publication and access to the data by end-users. Several different categories of users (user classes) are defined and shown in Figure 27.

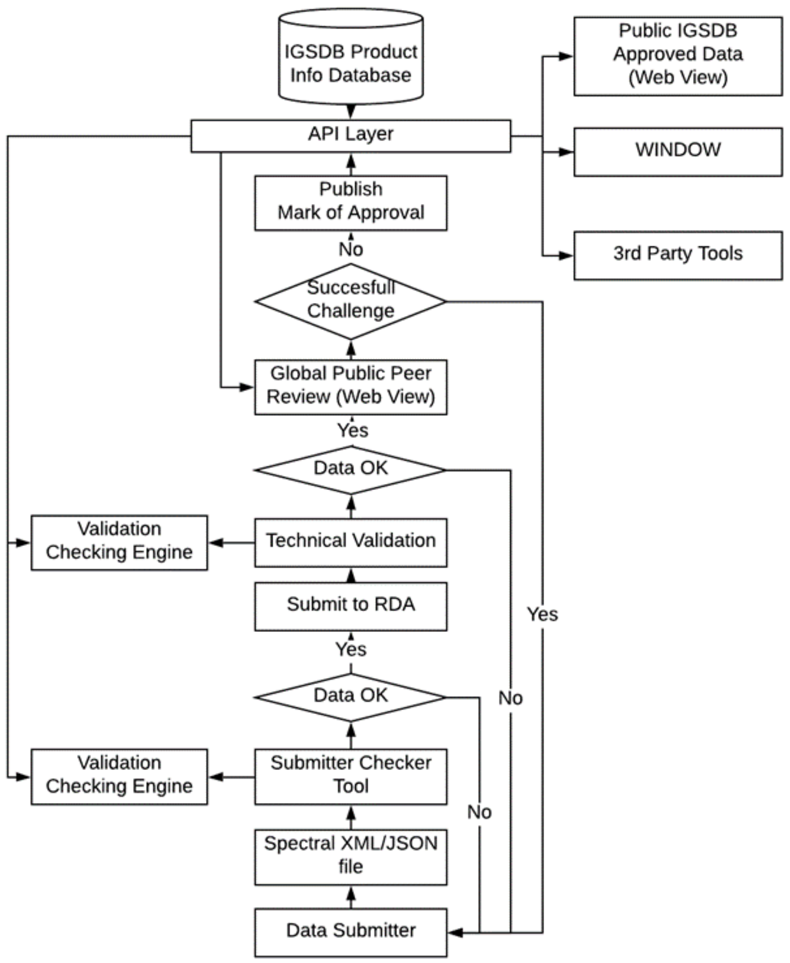


Figure 26. RDA Process Diagram for IGSDB Data

User Roles	Symbol	Description
Public	P	Public users who want to browse/search published products.
Data Submitter : Manufacturer	DS:M	A manufacturer who wants to submit data for their products.
Data Submitter	DS:C	A consultant or other third party who wants to submit data for one or more manufacturers.
Regional Data Administrator : Business	RDA:B	A manufacturer who has agreed to act as a regional administrator and facilitate part of the submission process.
Regional Data Administrator : Technical	RDA:T	A community member who has agreed to act as a regional administrator and facilitate part of the submission process.
Superuser	S	LBNL user(s) who administer the users and features of the CT.

Figure 27. User Classes for the IGSDB/RDA Web Tool

3.3.2 Establishment of Fraunhofer ISE as the European RDA

To introduce Fraunhofer ISE to the activities of a Regional Data Aggregator, LBNL shared its experience with and documentation of the existing submittal process and data formats for IGDB with Fraunhofer ISE. This process is still based on the processing of ASCII data files that are submitted by glazing manufacturers as email attachments to LBNL.

In consultation between NFRC, LBNL and Fraunhofer ISE, the legal framework for Fraunhofer ISE becoming an RDA for Europe was clarified. Whereas Fraunhofer ISE had originally proposed that it should address both the technical and business aspects of RDA work, closer legal scrutiny made it clear that most proposed activities of a “Business RDA” were essentially administrative, e.g. forwarding fees paid by the companies to NFRC. These are incompatible with the mission of Fraunhofer ISE as a research organization. Thus, the Statement of Work was revised and currently covers Phase 1 of the RDA implementation with Fraunhofer ISE as a technical RDA for Europe.

The contract between NFRC and the Fraunhofer-Gesellschaft on these RDA activities entered into force on 1.7.2020, initially for a period of one year. During that time, Fraunhofer ISE reviewed a total of 135 new data files and 53 modified data files from seven internationally active, European glazing companies, for four version updates of the IGDB. Direct interaction within the same time zone between the European RDA and the submitting companies had a beneficial effect on the technical quality of the spectra and correct observation of formal submission requirements (Milestone 1). Based on the positive experience of the first year, the terms were revised for the first amendment to the original contract, which became effective for a further year on 1.7.2021.

In Phase 1, the RDA collects measured optical data for glazing, reviews it critically and submits it to LBNL for peer review and further processing. This allows the RDA to be the single point of contact with LBNL for European glazing manufactures. They submit their data to the RDA, and the RDA

1. Verifies that the files match the submission data sheet
2. Verifies that the files can be imported into Optics
3. Presents any technical measurement or formal issues to the manufacturer, takes steps to resolve them, and iterates step 1-3 until no more issues are present
4. Consolidates all submissions and forwards them to LBNL.

In addition to these activities as a “Technical RDA”, the only non-technical RDA activity for Fraunhofer ISE is to disseminate information about NFRC and the IGDB in Europe. This work is ongoing, with regular presentations to ICG-TC10, in which all of the submitting European glazing companies are represented. The German Glazing Manufacturers’ Association, Bundesverband Flachglas was also informed about the IGDB with a dedicated presentation by Fraunhofer ISE.
The removal of most activities as a “Business RDA” has reduced the income which is anticipated to be generated by Fraunhofer ISE’s activity as the European RDA. This is reflected by the budget figures in the Section on Targeted Projects in the Annex of this report.

3.3.3 RDA preparation for the IGSDB

The development by LBNL of the IGSDB Web Tool, which includes web-based management of data submission and peer review, is well advanced and the first public version of the tool is expected to be released during the first quarter of 2022. To gain experience with the IGSDB Web App, which allows potential submitters to check the format compliance of their data files with IGSDB requirements, several members of the Fraunhofer ISE team registered as beta testers. They found use of the App to be straightforward.

To prepare for work as an RDA to the IGSDB (in addition to the IGDB), LBNL introduced Fraunhofer ISE to its web-based “Checkertool”, which automatically checks compliance of submitted files with formal IGSDB requirements and technical criteria. Fraunhofer ISE first applied the Checkertool for its initial screening of data submitted for the v84 update of the IGDB.

As the submission of data files on so-called “complex glazing” (light-scattering glazing, light-redirecting elements and solar-shading products) to the IGSDB is not foreseen until after the end of the ICON project, Fraunhofer has not yet been involved as an RDA for the submission of this type of glazing or shading product data. However, it is anticipated that data submission review as an RDA for these more optically complex products will be part of the next amendment to the RDA contract between NFRC and Fraunhofer ISE for the period from 1.7.2022 onward.

3.4 WP 4 - Optical measurement and data-processing methods applying bi-directional data

Contributors from Fraunhofer ISE: Helen Rose Wilson (WP leader), Bruno Bueno
Contributors from LBNL: Jacob Jonsson (WP leader), Eleanor Lee, Taoning, Wang, Greg Ward; junior researcher Maryna Bilokur as a post-doc

Results anticipated from WP4 in SoW: "Upgraded measurement and data-processing methods to determine the full range of solar-optical properties of advanced building-envelope products. Newly created and/or extended, internationally recognized methods to measure and model the optical, thermal and energy-related characteristics of complex fenestration systems will be available. There will be mutually validated measurement methods for optical component characteristics which take spectral, polarization-dependent, angle-dependent (incident and outgoing angles, including angular resolution) properties into account and allow application-relevant integrated quantities (spectrally weighted, spatially integrated, unpolarized) to be determined."

3.4.1 Introduction

Within WP4, optical measurement methods were improved and validated in separate campaigns addressing diffuse (or light-scattering) glazing and solar-shading, as different measurement aspects are important for these two different components of complex fenestration systems (CFS). They are thus presented in two different sub-sections. The final sub-section addresses a specific data-processing method that applies to BSDFs for both types of CFS components, namely the creation of BSDF data files with the Klems angle base according to WINDOW XML format, and includes the treatment of spectral data.

3.4.2 Measurement and data processing for diffuse glazing

Validation of integrating-sphere measurements
The NFRC-funded research project on integrating-sphere measurement of diffuse glazing[1*] was motivated by the recent commercial availability of integrating spheres designed to measure such materials and was completed with several significant outcomes. Most significant was the implementation of our suggested procedures for measurement of light-scattering (or "diffuse") glass in NFRC documents 300[2] and 301[3] which specify measurement of solar-optical and thermal IR properties of glazing products. Emissometers were determined to be suitable instruments to measure the emissivity also of rough surfaces with low-e coatings, and the use of gold-coated integrating spheres in

[1*] Jonsson, J.C., Wilson H.R., Bilokur, M, (2021) „ Preliminary report on LBNL 2019 inter-laboratory comparison for laboratories submitting scattering glazing data to the CGDB" LBNL web site: https://windows.lbl.gov/2019-complex-glazing-ilc, direct link https://windows.lbl.gov/sites/default/files/Downloads/CILC2019report.pdf
[2] National Fenestration Rating Council Document NFRC 300-2020[E0A0], NFRC 300-2020[E0A0]: Test Method for Determining the Solar Optical Properties of Glazing Materials and Systems 2020
[3] National Fenestration Rating Council Document NFRC 301-2020[E0A0], NFRC 301-2020[E0A0]: Standard Test Method for Emittance of Glazing Products, 2020

the IR for emissivity determination based on measured reflectance spectra is now explicitly allowed. The inter-laboratory comparison exercise (ILC) included both the new, commercially available integrating spheres and the large, customised spheres that have been used at Fraunhofer ISE for several decades. The ILC showed great agreement for normal-hemispherical transmittance and reflectance measured with integrating spheres that were specifically designed to measure this type of sample in the solar spectral range, as demonstrated in Figure 28. This represents a significant improvement on the situation when the commercially available integrating spheres had sample apertures that were too small (typically with diameters of 25 mm or less) for this type of sample, resulting in integrated light and solar transmittance and reflectance values that were up to 0.1 too low (absolute)[1]. Even the agreement for the normal-normal and normal-diffuse components transmittance and reflectance is quite good for homogeneous (as distinct from geometrically structured) samples. As a result, allowable tolerances of 0.02 and 0.03 for normal-hemispherical transmittance and reflectance of diffuse glazing have been added to NFRC document 302 on the “Verification Program for Optical Spectral Data”, with the tolerances for the normal and diffuse components being 0.01 higher.
Haze, which is defined as the ratio of normal-diffuse to normal-hemispherical visible transmittance, is another commonly used metric that can be derived from the measured quantities. The calculated haze properties from the measurements did not agree as well, this was expected as it is dependent on the geometry of the measurement instruments. A control for this had been implemented but it did not sufficiently normalize the result. A detailed investigation of the BSDF of the samples and instrument geometries concluded that the approximation made in the correction, where the light beam in the integrating sphere of the spectrophotometer was considered to have a negligible cross-section, was probably too crude for the correction to work. Mathematical analysis of the haze calculation showed how uncertainty in the measurements were amplified in the calculation. It is still believed that haze can be a useful metric, but care must be taken when comparing results measured in different types of equipment.

[1] Wilson, H.R., Elstner, M. „Spot Landing: Determining the Light and Solar Properties of Fritted and Coated Glass“. Challenging Glass 6 - Conference on Architectural and Structural Applications of Glass, Louter, Bos, Belis, Veer, Nijsse (Eds.), Delft University of Technology, 2018. ISBN 978-94-6366-044-0, https://doi.org/10.7480/cgc.6.2134

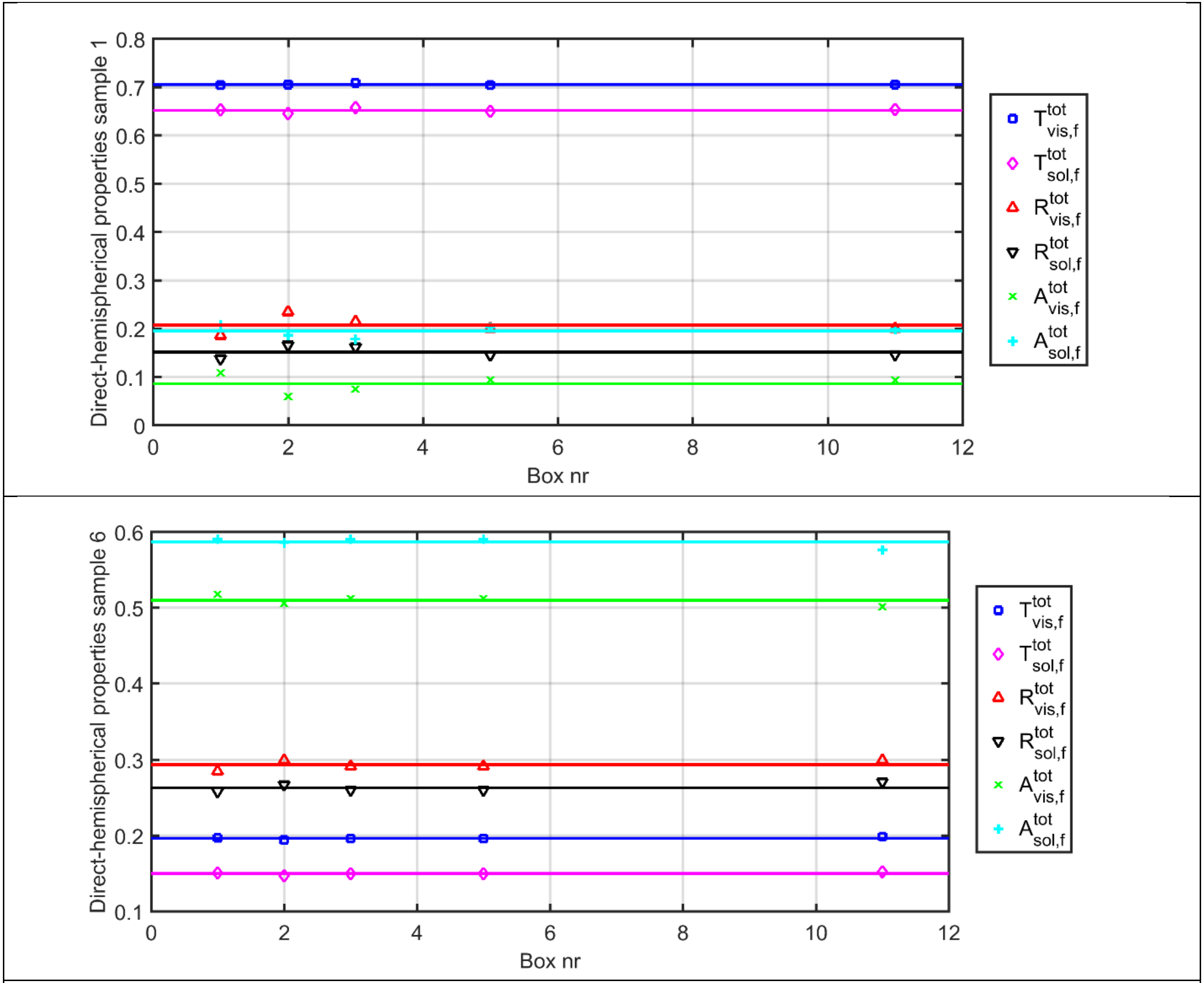


Figure 28: Results from 5 participants showing agreement for the direct-hemispherical properties of samples 1 (a laminate with a strongly scattering interlayer - above) and 6 (a patterned glass pane with a low-e coating - below).

Normal-conical transmittance as a new metric:

To supplement the ILC, BSDF measurements of the glass samples were made at Fraunhofer ISE, using the 3D-scanning pgII goniophotometer (Figure 31) and analysed by introducing a new metric. This was defined to summarize information on light-scattering behaviour in a compact form but in greater detail than is possible using normal-normal and normal-hemispherical transmittance alone. “Normal-conical transmittance” represents the proportion of normally incident radiation which is transmitted within a cone with a specified half-angle that is centred on the outgoing normal to the surface. It is readily calculated from a BTDF by integration over a spherical “cap” conforming to this description (see Figure 29).

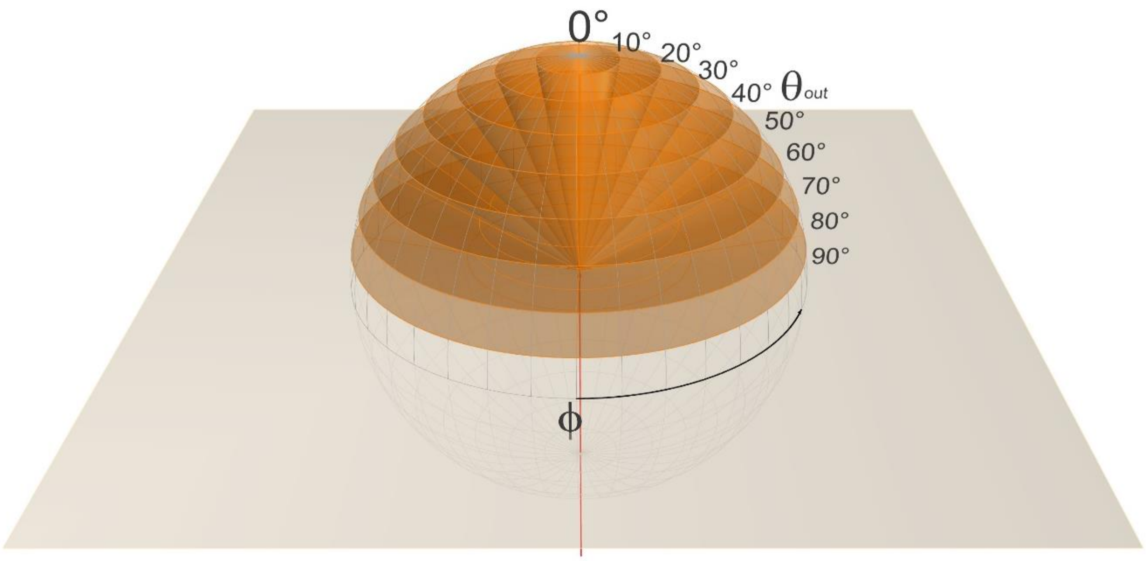
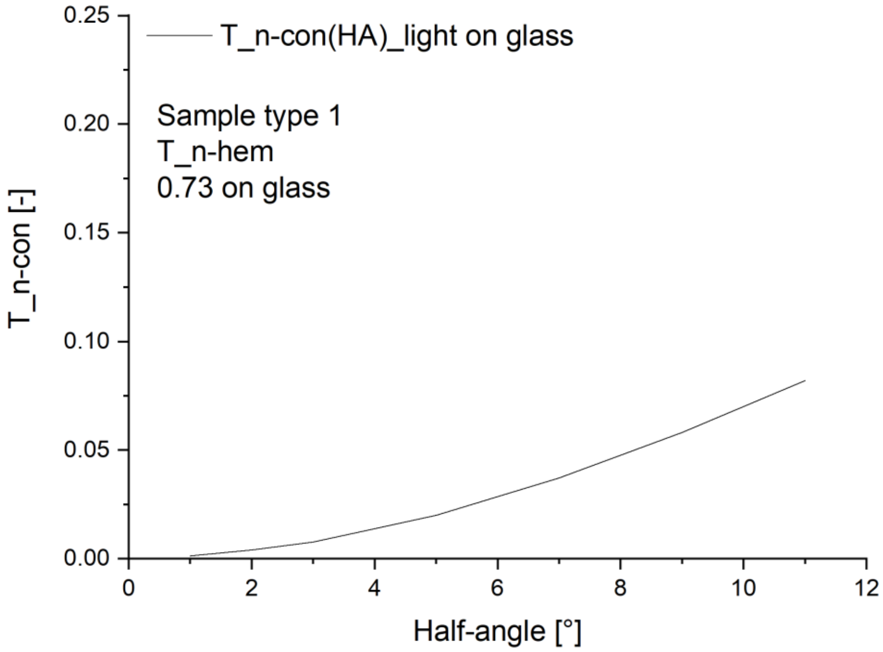


Figure 29: Concept of the new metric, normal-conical transmittance, referring to the proportion of normally incident light transmitted within a cone that is centred on θ_{out} = 0° and is characterised by a half-angle, which is equal to θ_{out} in this specific case of normal incidence. The well-established quantity, normal-hemispherical transmittance, corresponds to one limit of this metric, with a half-angle of 90°. The normal-normal transmittance ideally corresponds to the normal-conical transmittance with a half-angle of 0° but in laboratory integrating spheres, the effective half-angle is typically up to about 5°.

A graph of the normal-conical transmittance versus the half-angle spans the range from normal-normal transmittance (ideally, with a half-angle of 0°; in integrating-sphere practice with half-angles typically up to about 5°) to normal-hemispherical transmittance with a half-angle of 90°. By analogy, direct-conical transmittance (or reflectance) can be defined for non-normal directions of the incident and outgoing radiation, but then the range of meaningful half-angles (HA) is restricted to HA < (90° - θ_{out}), where θ_{out} describes the direction of the central axis of the cone.

Figure 30 shows normal-conical transmittance plots for the same two sample types as Figure 28, clearly visualizing the difference in scattering behaviour of a large-angle scatterer (sample 1) and a relatively small-angle scatterer (sample 6). Due to the marked increase in the T_n-con value of sample 6 for half-angles up to 5°, the value obtained for T_n-n (and thus T_n-dif and the haze value) can be expected to vary sensitively with the geometrical configuration of the measuring instrument. By contrast, the haze value determined for sample 1 is quite “robust”, as was demonstrated by the ILC results.



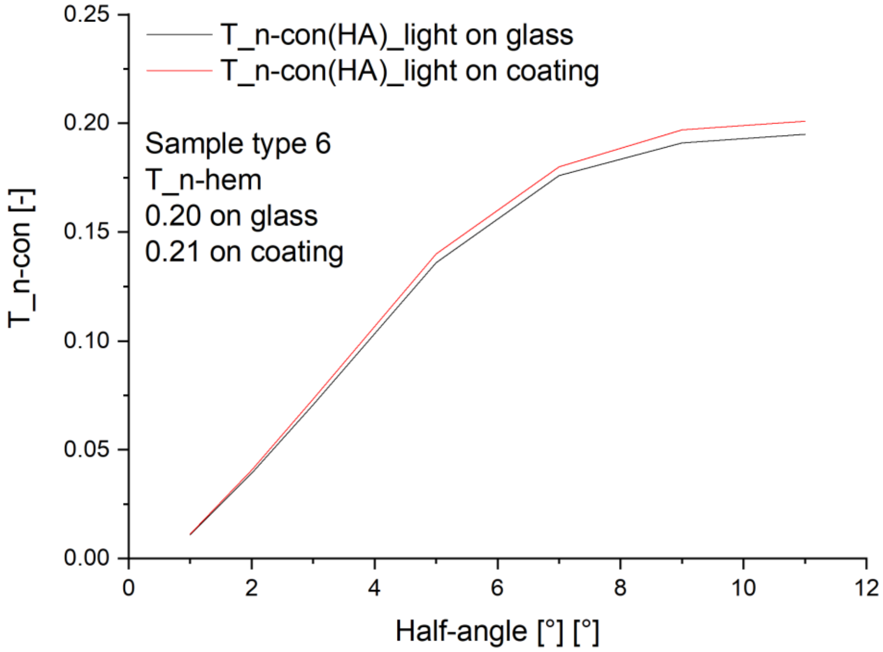


Figure 30: Normal-conical transmittance versus cone half-angle for samples 1 (a laminate with a strongly scattering interlayer - above) and 6 (a patterned glass pane with a low-e coating - below).

Data processing and modelling multiple-pane glazing

New capabilities to allow the Berkeley Lab WINDOW software to use diffuse glazing measured according to these new methods in glazing systems were developed and implemented in a beta version of WINDOW. Testing was successful showing the impact of scattering layers in glazing systems and yielding realistic results for a range of different configurations. Inclusion in the official branch of WINDOW 7.8 is scheduled for 2022.

A four-flux model was created where a light-scattering sample could be modelled as multiple layers, e.g. substrate, diffuse layers like an acid-etched surface, a fritted surface, or a diffuse interlayer. With such a model it would be possible to replace the substrate properties and get a new result for the whole stack. The results presented in the four-flux report are promising, but the complexity as well as the fact that nothing of the formalism already exist in Optics or WINDOW makes it hard to predict how much effort it would be to integrate into LBNL's software tools. Having experimental data on samples with the same scattering component but on different substrates will be useful for future theoretical work. The paper by Maryna Bilokur detailing the process is being prepared for publication[1*].

The ILC work in the NFRC-funded research project was led by LBNL (Jacob Jonsson) and Fraunhofer ISE (Helen Rose Wilson) with collaborators in Saint-Gobain Glass (Loïs-Brian Clemenceau), Guardian Corporation (Jason Theios), Eastman (Julia Schimmelpenningh), NSG Europe (James Farmer), AGC Europe (Ingrid Marenne), INISMa (Christine Kermel), Viracon (Brian Dawley), IFT Rosenheim (Michael Freinberger), OMT (Serge Timmermans), Vitro formerly PPG (Mike Buchanan).

3.4.3 Measurement and data processing for solar-shading materials and devices

Correction for photogoniometer dark signal in measurements

For glare analysis, it is necessary to know how well a material prevents incident light from being transmitted, which implies accurate determination of low transmittance values. In this measurement range, the effect of a “dark signal”, often the result of thermally induced noise in the detector, needs to be taken into account. Using the “phirot2” sample holder for the pgII goniophotometer at Fraunhofer ISE (Figure 31), which was acquired with ICON equipment funding, it is now possible to make dark measurements, reference beam measurements and sample BSDF measurements of one sample in a single automated sequence, without the need for personal intervention after the initial sample mounting. A correction procedure, taking account of the dark signals before and after the sample measurement, has been implemented and is now part of the standard procedure at Fraunhofer ISE.

[1*] Bilokur, M., Jonsson, J.C., Four-flux radiative transfer model to determine optical performance of the unknown scattering layer in a multilayer glazing sample, To be submitted to Optics Communication

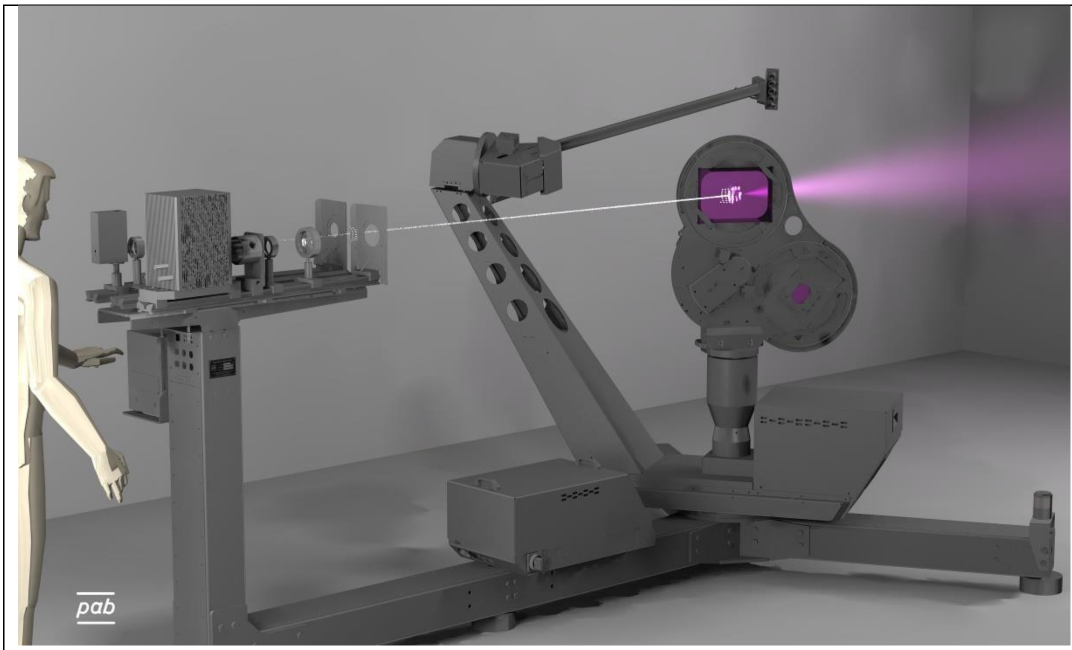


Figure 31: pgII goniophotometer with the new *phirot2* sample holder, with holders for two different samples and an aperture for the reference beam. A completely automated measurement sequence for one sample, including reference beam determination and dark signal measurement, can be run without human intervention by leaving the second sample holder empty. This allows the night to be used effectively for long measurement sequences. This sample holder was acquired by Fraunhofer ISE with ICON equipment funding. Source: Peter Apian-Bennewitz, pab advanced technologies Ltd.

BSDF generation procedures and applications

Within the IEA SHC Task 61 on "Integrated Solutions for Daylighting and Electric Lighting"[1], LBNL and Fraunhofer ISE, together with other institutions, prepared a white paper on BSDF generation procedures and applications, which was published in January 2021 as Technical Report T61.C.2.1[2]*. The white paper was intended to stimulate discussion and critical review of these procedures internally within the IEA task and then also externally by research and industry.

The white paper starts by summarizing fundamental concepts and term definitions related to BSDFs. It continues by defining what is generally understood as low- and high-resolution BSDFs, and presents the BSDF angular basis and file formats currently used by simulation tools. The white paper then describes procedures to obtain BSDFs for different types of fenestration systems,

[1] http://task61.iea-shc.org/

[2]* Geisler-Moroder, D. (Ed.), Lee, E.S., 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 - A Technical Report of Subtask C, IEA SHC Task 61 / EBC Annex 77. https://task61.iea-shc.org/publications. DOI: 10.18777/ieashc-task61-2021-0001

including transparent systems, homogeneous or small-pattern light-scattering systems, matt or glossy blinds and grids, macroscopic prismatic systems, and micro-structured or nano-structured systems. These procedures combine experimental techniques, such as photogoniometer and integrating sphere measurements, with numerical techniques, such as interpolation and raytracing modelling. The paper also offers recommendations for BSDF resolutions and formats for simulation tools, depending on the type of system – microscopic or macroscopic - and intended use of the BSDF data. Output from simulation tools include illuminance and luminance data for the assessment of daylight availability, lighting energy use, visual comfort, indoor environmental quality, and other visual and non-visual performance parameters related to daylight from windows and skylights. Output also includes transmitted solar irradiance which can enable more detailed analysis of thermal comfort and solar loads on indoor surfaces.

<u>Analysis and evaluation of BSDF-based characterization of daylighting systems</u>

Also within IEA SHC Task 61, both LBNL and Fraunhofer ISE contributed to a second technical report, T61.C.2.2[1]*, which was published in October 2021. It documents the experimental equipment and procedures which both laboratories regularly apply for BSDF measurements with their 3D scanning goniophotometers, depending on the type of sample to be characterized. Discussion between LBNL and Fraunhofer ISE in this context led to extension of RADIANCE options to accommodate samples with rotational symmetry of finite order (as distinct from isotropic samples with rotational symmetry of infinite order). It also contains the results of an inter-laboratory comparison to determine the BSDFs of two types of solar-shading samples. The BSDF of a woven solar-shade fabric, a twill weave with rotational symmetry of order 2, was measured directly. To obtain the BSDF of a venetian blind, usually the BRDF of the slat material was measured and this was subsequently combined with a geometrical model of the blind configuration. The data submitted by Fraunhofer ISE was measured using the pgII goniophotometer and corrected for the dark signal. BSDF datasets in Klems and tensor-tree (high-resolution) formats were automatically generated from the dark-corrected measurements with a script applying Radiance built-in interpolation routines. LBNL submitted its BSDF data also in Klems and tensor-tree formats, as well as supplying the sets of raw measured data.

A variety of metrics was applied to compare results from the different laboratories, whereby the point-in-time renderings, further images derived from them, the daylighting assessments and the glare metrics all benefited from the work within WP1. The applied metrics comprise:

- integrated light transmittance (hemispherical-hemispherical, 0°-hemispherical, 0°-0°, 30°-hemispherical, 30°-30°, 50°-hemispherical, 50°-50°),

[1]* Geisler-Moroder, D. (Ed.), Apian-Bennewitz, P., de Boer, J., Bueno, B., Deroisy, B., Fang, Y., Grobe, L.O., Jonsson, J.C., Lee, E.S., Tian, Z., Wang, T., Ward, G.J., Wilson, H.R., Wu, Y. „Analysis and evaluation of BSDF characterization of daylighting systems." T61.C.2.2 – A Technical Report of Subtask C, IEA SHC Task 61 / EBC Annex 77. https://task61.iea-shc.org/publications. DOI: 10.18777/ieashc-task61-2021-0012

- Klems representations of the BTDF for incidence angles of 0°, 30° and 50° and hemispherical illumination,
- point-in-time renderings of daylight in an office model at monthly intervals from the winter to the summer solstice, from which vertical eye illuminance (E_v) values, daylight glare probability (DGP), falsecolour luminance maps and glare source maps were derived
- annual daylighting simulations of another office model, from which workplane daylight autonomy, vertical illuminance at camera position, DGP and daylight glare index (DGI) were calculated

This selection of metrics, some of which are illustrated in Figure 33, could well prove to be a reference for future inter-laboratory BSDF comparisons, as the results for transmittance and daylight performance showed generally good agreement, whereas the glare metrics proved to be highly sensitive to the BSDF resolution and the representation of small, bright sources of glare.

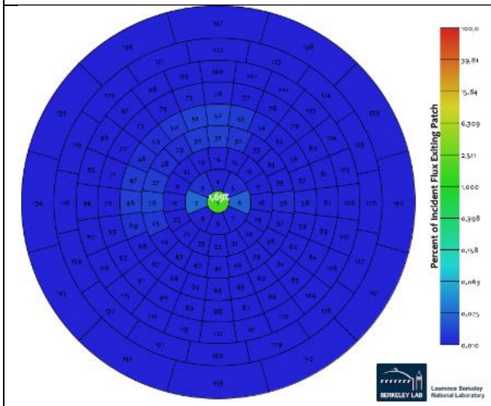
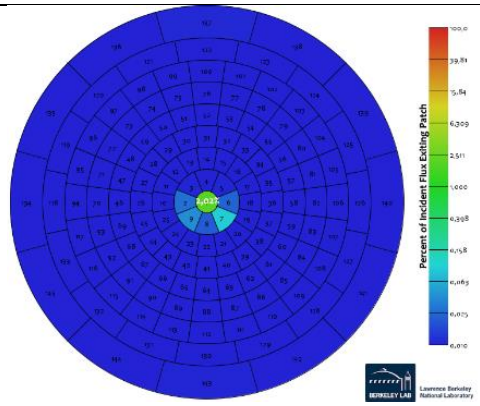
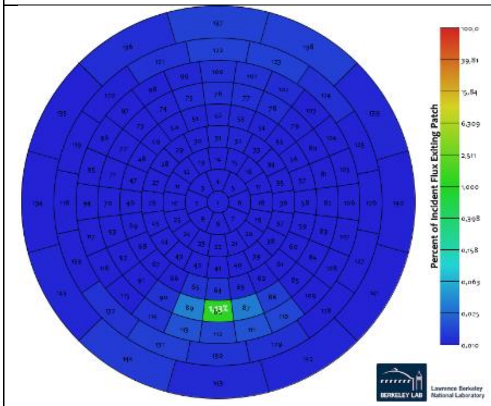
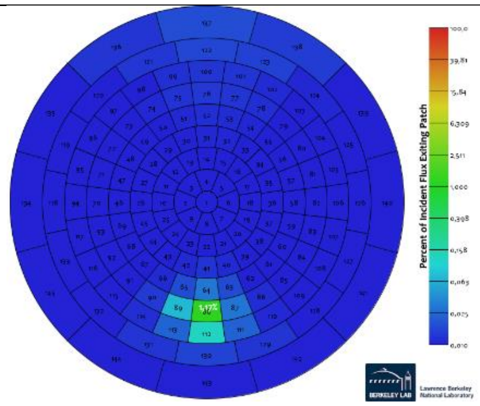
LBNL	Fraunhofer ISE
 BTDF, θ_{in} = 0°	 BTDF, θ_{in} = 0°
$\tau_{d\text{-}h}$ = 2.8%, $\tau_{d\text{-}d}$ = 1.69%	$\tau_{d\text{-}h}$ = 3.3%, $\tau_{d\text{-}d}$ = 2.02%
 BTDF, θ_{in} = 50°	 BTDF, θ_{in} = 50°
$\tau_{d\text{-}h}$ = 2.5%, $\tau_{d\text{-}d}$ = 1.13%	$\tau_{d\text{-}h}$ = 2.7%, $\tau_{d\text{-}d}$ = 1.17%

Figure 32: Results calculated by D. Moroder-Geisler from BSDF measurements at LBNL and Fraunhofer ISE: BTDFs in Klems format for θ_{in} = 0° and 50°, the direct-hemispherical and direct-direct transmittance values obtained by integrating the BTDF values. Source: T61.C.2.2[1]*, Images reproduced with kind permission of D. Geisler-Moroder, Bartenbach GmbH.

[1]* Geisler-Moroder, D. (Ed.), Apian-Bennewitz, P., de Boer, J., Bueno, B., Deroisy, B., Fang, Y., Grobe, L.O., Jonsson, J.C., Lee, E.S., Tian, Z., Wang, T., Ward, G.J., Wilson, H.R., Wu, Y. „Analysis and evaluation of BSDF characterization of daylighting systems.“ T61.C.2.2 – A Technical Report of Subtask C, IEA SHC Task 61 / EBC Annex 77. https://task61.iea-shc.org/publications. DOI: 10.18777/ieashc-task61-2021-0012

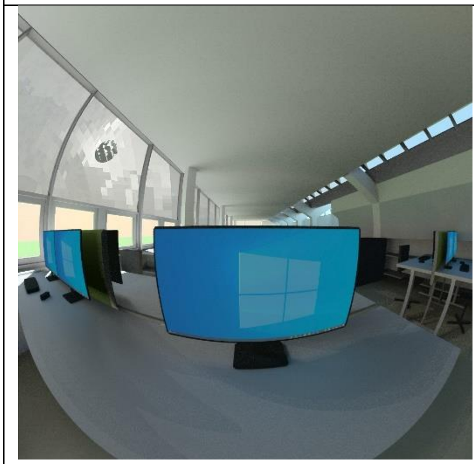
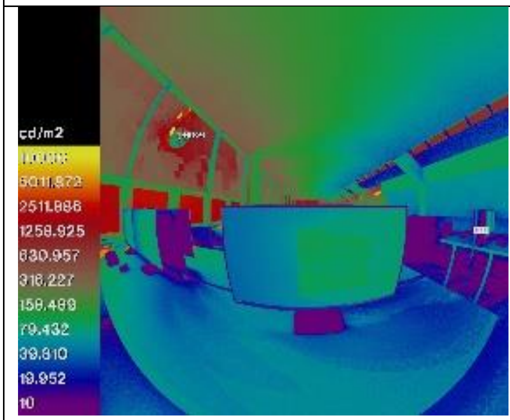
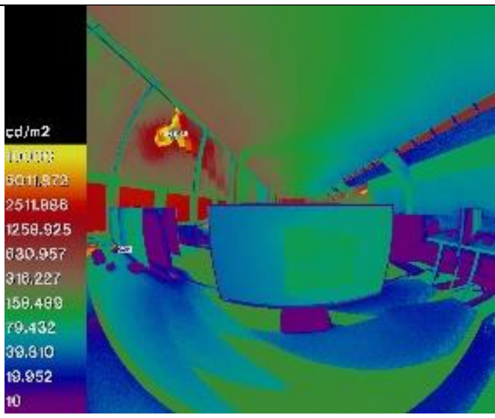
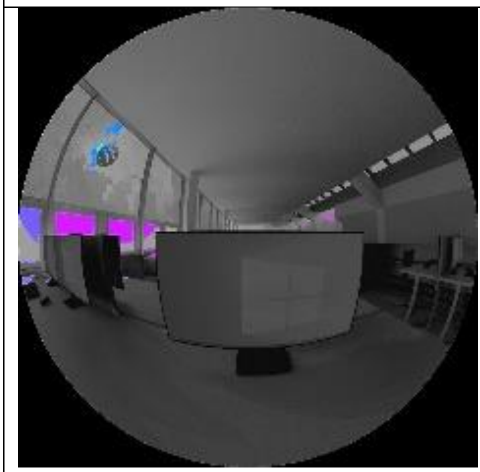
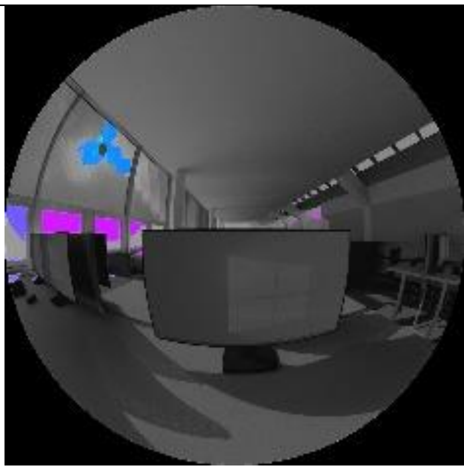
LBNL	Fraunhofer ISE
 point-in-time rendering	 point-in-time rendering
 falsecolor luminance	 falsecolor luminance
 glare sources identified by *evalglare*	 glare sources identified by *evalglare*
Ev = 593 lx, DGP = 0.28	Ev = 1145 lx, DGP = 0.38

Figure 33: Results calculated by D. Moroder-Geisler from BSDF measurements at LBNL and Fraunhofer ISE: Point-in-time rendering images of an office with a solar-shading screen characterised by the BTDFs, and the corresponding luminance and glare source images. High-resolution BSDF data sets applying peak extraction were used for the point-in-time rendering. Source: T61.C.2.2[1]*, Images reproduced with kind permission of D. Geisler-Moroder, Bartenbach GmbH.

3.4.4 Creating Klems coordinate system BSDF data files according to WINDOW XML format

The complex glazing database CGDB contains many XML files with BSDF data in them for light-scattering glazing and for solar-shading materials and systems. These were originally accessed and combined within the WINDOW program of LBNL. As a result of the work done within WP2, they are now also accessible via the metabase. Different pathways for creating the XML files with BSDF data according to the WINDOW XML format are described below.

3.4.4.1 Formatting, storing, and accessing BSDF data in the CGDB, the IGSDB and via the metabase

The XML schema holds the formal definition of the file format, but WINDOW and other programs that parse these XML files are not able to handle all possible options so having examples of a file that works in WINDOW is helpful. Downloading the latest version of CGDB from https://windows.lbl.gov/tools/cgdb/software-download should be a good source for full XML files that can be used by WINDOW.

The schema for the XML format is defined by BSDF-v1.7.7.XSD.

It consists of a header with information about the product, followed by the angle basis (e.g. the Klems coordinate system used in WINDOW) and a block defining each wavelength band (visible and solar), optical property (reflectance/transmittance) and sample surface facing the incident light during measurement (front/back). This block will come back in 8 permutations with all possible combinations of three variables

- Wavelength: This can be Visible or Solar
- WavelengthDataDirection: This has two parts, Reflection or Transmission,
- and Front or Back.

For each permutation there will be a 145 by 145 matrix conforming to the Klems representation with BSDF values in the data block. Each column corresponds to an incident direction and each row corresponds to the outgoing direction, resulting in all specular directions being located on the main diagonal.

The tail of the schema only closes the blocks started in the header.

[1]* Geisler-Moroder, D. (Ed.), Apian-Bennewitz, P., de Boer, J., Bueno, B., Deroisy, B., Fang, Y., Grobe, L.O., Jonsson, J.C., Lee, E.S., Tian, Z., Wang, T., Ward, G.J., Wilson, H.R., Wu, Y. „Analysis and evaluation of BSDF characterization of daylighting systems.“ T61.C.2.2 – A Technical Report of Subtask C, IEA SHC Task 61 / EBC Annex 77. https://task61.iea-shc.org/publications. DOI: 10.18777/ieashc-task61-2021-0012

3.4.4.2 Obtaining integrated IR properties for the header

The integrated thermal IR emissivity and IR transmittance are given as integrated values. For shade materials, the most common path to obtaining a thermal IR emissivity is to use an emissometer according to AERC 1.1 appendix E, which is available under https://aercnet.org/technical-documents/ . According to the revised version of NFRC 301 (see Section 3.4.2), either emissometers or gold-coated integrating spheres can be used to determine the integrated thermal IR emissivity and IR transmittance for light-scattering glazing.

3.4.4.3 Converting spectral data to the visible and solar wavelength bands

Spectral data can be used to calculate visible and solar properties according to NFRC 300 (see Section 3.4.2).

genBSDF is a Radiance routine that can generate Klems XML files as output. These are commonly created where optical properties of the elements are the spectrally integrated visible values. However, genBSDF is agnostic to this and if integrated solar values are used in the input model, the resulting BSDF will be a solar BSDF.

Radiance can also handle an interpolant format where the BSDF is represented by an ensemble of gaussian lobes which can be sampled using bsdf2klems to produce a Klems coordinate system BSDF XML file. Just as genBSDF is wavelength-agnostic, this is also true for bsdf2klems, so the wavelength property of the output data will match that of the input.

3.4.4.4 BSDFs in Klems format and sample symmetry

One quirk of bsdf2klems is that the sampling of the interpolant is carried out to match the Klems coordinates, which does not compress data for symmetric layers. This means that the resulting matrix might have different direct-hemispherical values where you would expect them to be identical. E.g. for an isotropic product where you would expect that for a given incident theta-value, all the incident phi-values would result in identical direct-hemispherical outgoing results, the randomness of sampling the interpolant for each incident direction will result in different values. Post-processing the BSDF to match the symmetry of the model or measurement can be helpful for users looking at the final BSDF to understand the symmetry of the product.

3.4.4.5 Spectral approaches taken by software tools using solar BSDF

As mentioned in Section 3.1.5, WINDOW converts solar data to do multilayer calculations in spectral data bands. The multi-layer calculations with diffuse layers are in WINDOW are, by default, carried out at 17 wavelength points (Preferences->Optical calcs->Spectral Data: Condensed spectral data). For the visible data points, the visible BSDF is used. For the other data points, a new BSDF matrix is calculated from the visible and solar matrices in the data file so that a solar integration over all these 17 points results in the same direct-hemispherical result as was given for the solar matrix. This is not ideal since the visible values have lost the energy information in the visible range.

However, for systems with spectrally selective coatings it is preferable do the multiple bands in this way than to do multi-layer calculations with only one integrated solar value for each layer.

The wavelengths in nanometers, where calculation is carried out when using the default 5 visible bands and 10 NIR bands of the WINDOW condensed calculation, are

300, 380, 460, 540, 620, 700, 780, 952, 1124, 1296, 1468, 1640, 1812, 1984, 2156, 2328, 2500

EnergyPlus does band-by-band calculation similar to WINDOW but with only two bands, visible and solar, and can use XML files with Klems format BSDFs in them for the window layers. Radiance can use the visible part of an XML file with a BSDF in Klems format.

3.5 WP 5 - Inclusion of newly developed complex fenestration properties in widespread applications (dissemination)

Contributors from Fraunhofer ISE: Bruno Bueno (WP leader until January 2021), Helen Rose Wilson (WP leader since February 2021)
Contributors from LBNL: Charlie Curcija (WP leader)

Results anticipated from WP5 in SoW: "Proposals for standards for product labeling, the initial building design phase and building permit application will have been completed. Simple but sufficiently accurate methods to represent the optical, thermal and energy-relevant properties of architectural glazing, solar-shading and active-solar products and integrated design solutions will have been developed. These methods will also communicate with the new database via semantic web interfaces. Methods to translate between existing standards with similar but not identical requirements will be available."

The original project framework provides a number of pathways for effective dissemination and application. Throughout the project, efforts were made to engage stakeholders and a wider audience in early versions of project products. A prime example is the cloud-based database of glazing and shading optical properties, IGSDB, which is being incorporated into the workflow of NFRC and AERC.

Some results of the ICON project can be classified as being of the specific types envisaged in the original SoW. These include:

- Proposals for standards for product labeling
    - The NFRC documents, 300, 301 and 302, which serve the same purpose as standards for window energy rating purposes, were modified as a result of the ILC conducted within WP4 on diffuse glazing.
    - A proposal to CEN TC 129, WG 9, to adopt similar modifications to EN 410 relating to light-scattering glazing, is planned. EN 410 contains procedures that are referenced by CE labels for the optical and thermal properties of glazing.

    - The proposed ISO NWI to update ISO 15099 will include revised and new methods developed in this project. ISO 15099 is a technical standard that is referenced in product labeling standards.
    - Product labeling is facilitated by easy access through the API/metabase to product data, to which labeling organizations like NFRC, AERC and ES-SO can connect.
- Simple but sufficiently accurate methods for integrated design solutions
    - The Fener[1] tool, which was extended during the ICON project, specifically addresses integrated evaluation of daylighting provision, glare protection and solar heat gain management
    - Tools developed in WP1 represent a benchmark for simpler methods of glare risk assessment, identifying whether their use is acceptable or inappropriate
- Methods to translate between existing standards with similar but not identical requirements
    - With the tools and data bases that we have developed further, e.g. IGSDB and WINDOW, it is possible for users to convert technical data according to one standard very easily to the values according to a similar but nonidentical standard.
    - The metabase provides for detailed references to technical standards and explicit options to use one or another equivalent standard on the same data set, which can in turn be accessed via the metabase.

Many of the other dissemination paths cannot be specifically attributed to the examples given in the SoW, but certainly fulfil the objective of making the results obtained in the ICON project more widely known. These engagements and activities include:

Active coordination between project leaders and ES-SO (European Solar-Shading Organization), AERC (North American window Attachment Energy Rating Organization), and WinCover (Australian window covering energy rating organization). We are also engaging with the North American National Fenestration Rating Council (NFRC) on the development of methods and software tools for the modelling of scattering glazing, such as fritted glass, diffuse, glass, etc. As part of this effort, we have held web-based meetings, participated in Task Groups and coordinated the development of joint database and software tool development.

A wider audience in the solar-shading sector is to be addressed by a webinar hosted by ES-SO on 23.02.2022, where members of the ICON team can present their results to technical representatives of the solar-shading industry in Europe, the U.S.A. and Australia. At the time of writing, already more than 60 persons had registered to attend the event, indicating widespread interest.

[1] **B. Bueno, A. Sepúlveda**. A specific building simulation tool for the design and evaluation of innovative fenestration systems and their control. IBPSA Building Simulation Conference, Rome 2-4 September, 2019

The WinCalc engine and python script implementation PyWinCalc, developed within the scope of WP1, is posted on GitHub and is promoted to a number of organizations from software development companies to Architectural and Engineering companies (AEC) and academia. The WinCalc engine is currently incorporated in WINDOW 8.0 software tool, which is posted as a Beta on the LBNL web site (https://windows.lbl.gov/therm-8-window-8), along with the new version of THERM 8.0.

WINDOW 8 now communicates with the cloud-based IGSDB, which in turn communicates with the metabase that was developed within the scope of WP2. Similarly, the optical data schema has been posted open-source on GitHub. Software developers have been informed of its presence in preparation for the planned follow-up project on the metabase, EQWIN-P.

Through WP3, European glazing optical properties are included in the IGDB with Fraunhofer ISE being RDA. The RDA activity by Fraunhofer ISE has facilitated direct contact to European glazing manufacturers and raised awareness of the features of the IGDB and IGSDB.

Development of ISO committee drafts (CD) and draft international standards (DIS) for updated windows and shading standards is part of overall activities within ISO TC163 and TC 160. Updating of the window calculation standard ISO 15099 has been proposed through the NWI proposal to establish separate working group (WG) under the subcommittee 2 (SC2) of TC163. This NWI is developed through the ASHRAE (American Society for Heating Refrigerating and Air-Conditioning Engineers), which serves as a Technical Advisory Group (TAG) for ISO TC163 and TC205. It is expected that the NWI will be submitted to ISO in the coming months. This new WG is expected to work on updating ISO 15099 to include revised and new methods, including methods developed in this project. In addition, active participation in ISO TC 163, SC1 (Test and measurement methods) led to publication of ISO 19467-2:2021, “Thermal Performance of windows and doors — Determination of solar heat gain coefficient using solar simulator — Part 2: Centre of glazing“ in 2021.

Measurement procedures and data formats for light-scattering materials developed in WP4 have been presented to the following glazing and solar-shading industrial associations in Europe and the U.S.A.:

- ICG-TC10 (International Commission on Glass – Tech. Comm. 10)
- Bundesverband Flachglas (BF - German Architectural Glazing Association)
- NFRC (National Fenestration Rating Council in North America)
- ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers)
- ICON industry experts from ES-SO (European Solar-Shading Organisation)
- ICON industry experts from AERC (Attachments Energy Rating Council in the USA)

The following tools, algorithms and/or proposals for standards have been documented for product characterization, the initial building design phase and building permit application:

- modifications to NFRC 300, 301, 302 specific to diffuse (light-scattering) glazing,
- tool for the design and evaluation of innovative fenestration systems and their control (FENER).

These tools have been presented to the professional bodies for building planners and architects in Europe and the U.S.A. at the following conferences:

- IBPSA (International Building Performance Simulation Association) conference in Rome, September 2019
- Thermal Performance of Building Envelopes Conference in Clearwater, FL, December 2019
- ASHRAE Virtual Winter Conference, February 2021
- virtual IBPSA conference, September 2021

Fraunhofer ISE as the European RDA for glazing products (WP3) was promoted regularly at the semi-annual meetings of ICG-TC10,

Dissemination of research results

Bibliographic details of the publications resulting from the ICON project can be found in the Appendix under “Publications in scientific journals”, “Public relations” and “Participation in conferences/ meetings/ seminars/ trade fairs”.

- Papers in peer-reviewed journals on the topics of
    - daylight simulation workflows incorporating BSDFs
    - benchmark of methods for annual glare risk assessment
    - model to determine optical performance of the unknown scattering layer in a multi-layer glazing sample (to be submitted)
- Technical Reports within IEA SHC Task 61 on
    - BSDF generation procedures for daylighting systems
    - analysis and evaluation of BSDF characterization of daylighting systems
- NFRC documents
    - Report on Inter-Laboratory Comparison of Light-Diffusing Glazing
    - Amendments to NFRC documents 300, 301, 302
- Individual and joint peer-reviewed conference papers presented at IBPSA 2019 and 2021 on
    - A building simulation tool to design and evaluate innovative fenestration systems and their control
    - Optical and Calorimetric Product Data in Building Information Modelling
    - Simulation Strategies for Annual Glare Risk Assessments based on the European Daylighting Standard EN 17037
    - Peak extraction in daylight simulations using BSDF data
    - Comparison of the latest window modeling methods in EnergyPlus

- Presentation of measurement procedures and data formats for light-scattering materials to glazing and solar-shading industrial associations in Europe and the U.S.A
    - ICG-TC10 (International Commission on Glass – Tech. Comm. 10),
    - Bundesverband Flachglas (BF - German Architectural Glazing Association),
    - NFRC (National Fenestration Rating Council in North America),
    - ES-SO (European Solar-Shading Organisation)
    - ASHRAE (American Society for Heating Refrigerating and Air-Conditioning Engineers)
    - AERC (Attachments Energy Rating Council in the USA)
- Posting of code on GitHub for
    - JSON schema for optical data sets
    - Open source code for WinCalc and PyWinCalc

Junior researchers

Details of work by junior researchers within the ICON project can be found in the Appendix under "Thesis work and academic degrees".

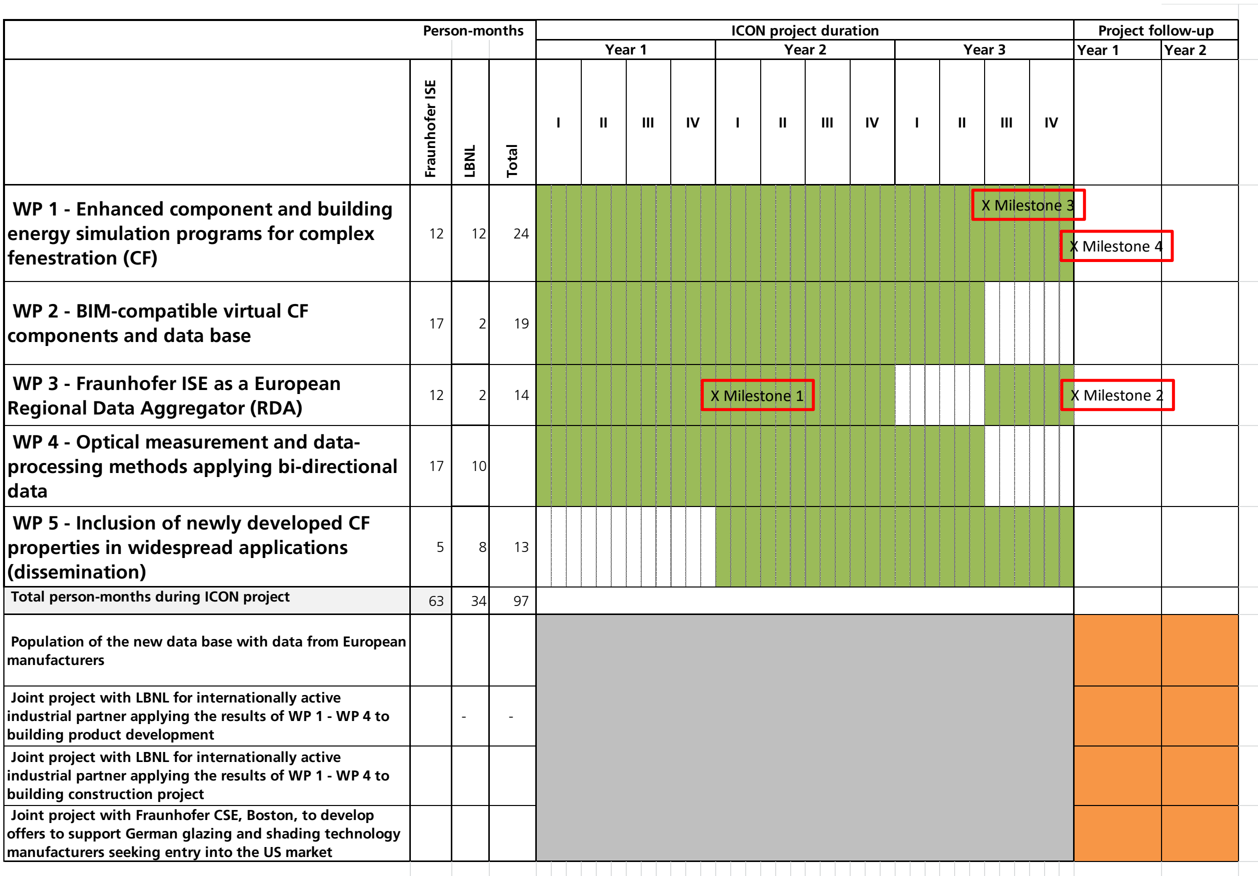
- Junior researcher, Luis Camilo Londono, contributed to WP1 as an M.Sc. student.
- Junior researcher, Abel Sepulveda, contributed to WP1, co-authoring a conference paper and a journal paper on the results.
- Junior researcher, Maryna Bilokur, contributed to WP4 as a post-doc and is preparing the journal paper mentioned there.

3.6 Summary and conclusions

Contributor from Fraunhofer ISE: Helen Rose Wilson (PI)

Contributor from LBNL: Charlie Curcija (PI)

Gantt chart



The Gantt chart above is the one that was included in the initial statement of work. During the course of the project, the total duration was extended by three months, primarily to allow the final meeting to be held in conjunction with the R + T Trade Fair, the leading trade fair for the solar-shading industry.

The four Milestones that were originally defined were useful as signposts throughout the project. However, during the course of the project, it proved necessary to move and/or modify some of them.

- Milestone 1: RDA system for IGDB (existing data base) defined and ISE established as RDA for Europe, respectively
    - Content unchanged; achieved in month 18 rather than month 12 due to length of trans-Atlantic legal negotiations

- Milestone 2: RDA system for IGSDB (new data base) defined and LBNL and ISE established as RDA for North America and Europe, respectively
    - Content unchanged; postponed from month 24 to after end of ICON project because external data submission to the IGSDB has not yet been implemented. However, the required tools are in preparation. The establishment of the IGSDB RDA structure will certainly be streamlined by the experience made in achieving Milestone 1.
- Milestone 3: Validation of intended interaction scheme for **building-envelope components** (WP1, WP2, WP4) - Example of complete processing chain for one performance indicator (e.g. SHGC) with validated measured data from WP4, entered into BIM-compatible format of WP 2 and further processed with the methodology of an extended building-component program of WP 1
    - Postponed from month 30 to month 36. The performance indicators chosen for this processing chain are the normal-hemispherical transmittance and reflectance, with multi-layer glazing units that includes a light-scattering (diffuse) glass pane being the selected type of building-envelope component. Work on this processing chain was divided into three segments. The validation of normal-hemispherical transmittance and reflectance values measured on light-scattering glass panes with integrating spheres (WP4 segment) and its further processing with a new feature of WINDOW 7.8 (WP1 segment) are documented in the NFRC report on the ILC that was accepted at the NFRC Fall meeting in 2021[1]. The WP2 segment addressing access to and transfer of such optical data via the metabase was demonstrated and documented in the joint conference paper presented at the IBPSA 2021[2].
- Milestone 4: Validation of intended interaction scheme for optical/thermal building performance (WP1, WP2, WP4) - Example of complete processing chain for one building performance indicator (e.g. daylight autonomy) with validated measured data from WP4, entered into BIM-compatible format of WP 2 and further processed with the methodology of an extended building energy/daylighting simulation program of WP 1
    - Achieved as planned by month 36 and documented in the IBPSA 2021 paper on Simulation Strategies for Annual Glare Risk Assessments based on the European Daylighting Standard EN 17037

[1] **J**onsson, J.C., Wilson H.R., Bilokur, M. (2021) “Preliminary report on LBNL 2019 inter-laboratory comparison for laboratories submitting scattering glazing data to the CGDB”, LBNL web site: https://windows.lbl.gov/2019-complex-glazing-ilc, direct link https://windows.lbl.gov/sites/default/files/Downloads/CILC2019report.pdf

[2] Maurer, C., Wacker, S., Bueno, B., Jonsson, J.C., Lamy, H., Bush, D., Shi, M., Sprenger, W., Mitchell, R., Wilson, H.R., Curcija, D.C., Kuhn, T.E. “Optical and Calorimetric Product Data in Building Information Modelling”. Proceedings of Building Simulation 2021, International Building Performance Simulation Association, Bruges, September 1-3, 2021

The key achievements are:

- Review of standards for calculating the heat transfer through fenestration systems, comprising
    - Comparison of the ISO 15099, ISO EN 52022-1 and ISO EN 52022-3 standards.
    - Comparison of the implementation of the ISO 15099 Standard in different building simulation programs.
    - Sensitivity analysis of window attachments' features on their thermal performance (U-value, Gtot), based on independent implementations of ISO 15099 into tools by LBNL and Fraunhofer ISE
- Review of the current state of the art in the field of measurement and simulation characterization of daylighting systems by bidirectional scattering distribution functions (BSDFs), and definition of commonly used BSDF data resolutions.
- Review of empirically based procedures for generating BSDF data sets for façade systems for later use in lighting simulation software.
- Recommendations for adequate characterization methods and BSDF resolutions for different classes of systems: transparent systems, homogeneous or small pattern diffusing systems, diffuse or specular blinds and grids, macroscopic prismatic systems, and micro- or nano-structured systems.
- A review of simulation workflows for energy, daylighting and glare analysis based on data-driven bi-directional scattering distribution functions (BSDFs).
- A benchmark of state-of-the-art methods for annual glare analysis in terms of computational time (CPU time) and accuracy.
- A peak extraction algorithm in Radiance to separate light transmittance peaks from the rest of BSDF data. The algorithm treats the surface for a sample ray as purely specularly transmitting, i.e., the surface transmits the ray unperturbed. Then the result is modified by the direct-direct transmittance value in this direction that is computed from the BSDF data, to avoid double-counting of near-specular transmission.
- Strategies to reduce the computational time of glare calculations without compromising the accuracy of glare calculations. Different Radiance-based methods, and analytical isotropic fabric systems are parametrized in terms of specular/diffuse scattering components and cut-off angle, are applied.
- A workflow that can be easily implemented in building simulation programs in order to perform annual glare risk assessments based on the Daylight Glare Probability (DGP) method. The DGP method has been used in the preparation of the European Daylighting Standard EN 17037 to recommend glare protection classes of shading devices for different situations (climate, façade orientation, window size, view position and direction). By implementing the DGP method, building simulation programs can be used to make design decisions on

conflicting functions of fenestration systems, including glare protection. A case study is presented to illustrate the proposed workflow.

- Identification of still open issues in BSDF characterization of daylighting systems and their application in lighting simulation tools.
- WINDOW 7.8 updated to integrate normal-normal and normal-diffuse spectra of the type measured in the ILC for light-scattering glazing of WP4
- WinCalc open-source calculation engine updated and posted on GitHub
- PyWinCalc Python script-based open-source tool, with the communication to the alpha version of the IGSDB developed and posted on GitHub
- Development of a cloud-based database, IGSDB (International Glazing and Shading Database) for glazing and shading data to the stage where the alpha version of IGSDB with glazing data was developed and posted on the heroku cloud server.
- opticalData.json, a JSON schema with a format which covers all optical data that are currently relevant to building-envelope performance, has been developed and posted open-source on GitHub. At the same time, this JSON schema is well suited to be used by software companies.
- Establishment of Fraunhofer ISE as the RDA for European manufacturers submitting data to the IGDB
- Successful completion of an inter-laboratory comparison (ILC) to validate the optical procedures to characterize diffuse glazing samples
- Modification of NFRC 300, 301 and 302 to reflect the findings of the ILC
- Proposal to CEN TC 129, WG 9 to adopt similar modifications to EN 410 relating to light-scattering glazing
- Implementation of an experimental procedure and data post-processing to correct for a dark signal in photogoniometric measurements
- Publication of a white paper on BSDF generation procedures and applications within IEA-SHC Task 61
- Publication of a report on the analysis and evaluation of BSDF characterization of daylighting systems within IEA-SHC Task 61
- Ongoing consultation between ICON project leaders and ES-SO (European Solar-Shading Organization), AERC (North American window Attachment Energy Rating Organization) and NFRC (North American National Fenestration Rating Council); occasional exchange with BMAA (Blind Manufacturers' Association of Australia)
- Inclusion of methods developed in this project in ASHRAE Fenestration Technical Committee TC 4.5, under the Calculation Procedures Subcommittee.

- Presentation of measurement procedures and data formats for light-scattering materials to glazing and solar-shading industrial associations in Europe and the U.S.A.
- Presentation of tools developed within ICON to professional bodies for building planners and architects in Europe and the U.S.A at conferences organized by IBPSA
- Involvement of junior researchers

The main challenges were:

- Delays in completing legal negotiations between Fraunhofer ISE and NFRC to implement Phase 1 of Fraunhofer ISE becoming the European RDA
- Delays in receiving results from the ILC on light-diffusing glazing that were exacerbated by the effects of the corona pandemic
- Different levels of structural maturity in rating organizations for the glazing and the solar-shading sectors. As a result, the original plan for Fraunhofer ISE to become a European RDA for AERC could not be implemented within the ICON project duration.

Further research needs and perspectives are:

- Full deployment of production version of IGSDB and the metabase
- Access to ES-SDA via the metabase
- Wider dissemination of developed software tools and databases
- Customized tools to make the data that is accessible through the metabase valuable for different users
- Resolution of still open issues in BSDF characterization of daylighting systems and their application in lighting simulation tools
- Establishment of Fraunhofer ISE as the RDA for European manufacturers submitting data to the IGSDB, including further development and implementation of the associated online tools

4 Transfer of research results into application

4.1 Applications and markets

The following (prospective) applications have emerged from the research results so far:

- access to product data for glazing and shading products from different data bases through a single entry point and in a consistent format through the metabase
- reliable assessment of glare-protection potential of shading products based on photogoniometric measurement and BSDF interpolation procedures
- validated measurement of transmittance and reflectance of light-scattering building-envelope materials using integrating spheres
- validated BSDF measurement procedure, including correction for dark signal
- BIM-compatible data formats and cloud-based data base
- Software tools with defined API that calculate the thermal and optical performance of glazing and shading systems and communicate with metabase
- Extension of existing software tools (see above) that model whole building energy performance to utilize new component software tools to assess annual energy performance contribution of windows and façade components.

The related (prospective) new products/processes/services and respective users are:

- product screening services based on the metabase, provided by LBNL or ISE to architects and building planners
- BSDF-based glare assessment services, provided by LBNL or ISE to building envelope product developers and building planners
- services based on BIM-compatible data formats above, provided by LBNL or ISE to building planners, architects, engineering firms in building design trade, construction companies, non-governmental organizations in the field of net zero energy and green buildings
- Web-based tools to help homeowners, architects, engineers and other building professionals in early design efforts to design better energy-efficient buildings
- metabase API, allowing manufacturers to market products with the potential to save energy and provide better comfort
- Updated international standards for use by measurement laboratories and manufacturers preparing data sheets

- Connecting metabase to an expanded list of component information, such as thermo-physical properties, including hygrothermal properties and their enhanced access through metabase API, for use by architects and building planners.

The ICON team has identified related competitive (dis)advantages, strengths/weaknesses, opportunities/risks for LBNL and Fraunhofer ISE as providers:

- competitive advantage – mutual recommendation among ICON partners to clients from the respective continent
- competitive disadvantage – fee structure to cover infrastructure of a research institute (but not applicable to services with a unique selling point resulting from infrastructure like a large photogoniometer)
- risk associated with funding of long-term maintenance for the metabase

Competitive (dis)advantages, strengths/weaknesses, opportunities/risks associated with the applications listed above include the following:

- competitive advantage – consistent data on complex fenestration system components from different sources due to access through the metabase
- competitive disadvantage – indirect access via metabase demands compliance with input/output conventions
- risk of non-acceptance by potential clients and continuation of current fragmented situation

Related relevant (prospective) commercial players include:

- manufacturers or manufacturers' associations with their own data bases: In the case of this ICON project, the desired strategy is collaboration and compatibility with the metabase, which is already being established with NFRC, ES-SO and AERC. Interest in similar collaboration has also been expressed by an executive of AFRC (Australian Fenestration Rating Council) and BMAA (Blind Manufacturers' Association of Australia).
  Ubiquitous Energy, a PV glazing start-up, is following up collaboration with LBNL by ramping up its commercial production of PV glazing and preparing to enter the markets
- building planners, architects, engineering firms in building design trade, construction companies
  - PAWS – Partnership for Advanced Window Solutions
- non-governmental organizations in the field of net zero energy and green buildings:
  - NEEA – Northwest Energy Efficiency Association
  - Efficiency Vermont –
  - ASHRAE – American Society for Heating, Refrigerating, and Air-Conditioning Engineers

Many results of this project have targeted wider use by the building professional community, benefiting from feedback by the ICON industry experts. The most important key achievements so far are:

- Operational metabase and functioning API with connection to two child database connection (IGSDB and TestLab Solar Facades Database)
- IGSDB (North American database of glazing and shading products) Beta service with defined API (accessible and available)
- Open source WinCalc glazing and shading calculation engine with defined API
- PyWinCalc python based code that allows for running WinCalc with IGSDB records and automating parametric studies
- Open-source WinCalc glazing and shading calculation engine with updated diffusing glazing calculation algorithms
- IGSDB extended to include the metabase GraphQL API
- RDA scheme established in North America with LBNL as the technical partner and two organizations as the business partners (NFRC for windows and AERC for window attachments)
- RDA scheme established in Europe for the IGDB with Fraunhofer ISE as the technical partner and NFRC as the business partner for windows
- Procedures to characterize thick diffuse glazing layers by measurement and calculation documented in NFRC documents 300, 301 and 302
- Proposal to CEN TC 129, WG 9 to adopt similar modifications to EN 410 relating to light-scattering glazing
- Proposed New Work Item for ISO to establish windows WG and to update windows and shading standards. Currently proposed to be established.
- Improved procedures within the Radiance ray-tracing program to process BSDF data for solar-shading textiles
- Improved procedures within the Radiance ray-tracing program to evaluate glare-protection properties of solar-shading textiles
- Review of standards for calculating the heat transfer through fenestration systems
- Comparison of simulation interfaces in terms of heat transfer through fenestration systems, daylighting and glare.

Challenges

- Relatively young organizations representing the solar-shading industry in the USA, Europe and Australia have developed different strategies and structures. As a result, technical (and legal and economic) differences meant that the aspired cross-licensing of approved data records in IGSDB and ES-SDA from AERC, ES-SO and WinCover could not be achieved within the timeframe of the ICON project.

<u>Perspectives for the transfer of research results into applications</u>

As indicated above, many of the research results relating to glazing products have already been transferred into applications, benefiting from close collaboration with NFRC. This organization is now more than 30 years old, such that it already has a wide membership base and well-established organizational structures that allowed it to adopt and transfer ICON research results quickly. The organizations representing the solar-shading industry are significantly younger and at the same time, many of the products they market are optically more complex. With time, however, it is expected that ICON research results will also be adopted by the solar-shading sector.
A first step is being taken with a webinar hosted by ES-SO on 23.02.2022, where members of the ICON team can present their results to technical representatives of the solar-shading industry in Europe, the U.S.A. and Australia.
Another opportunity would be to make use of a Fraunhofer ISE strategic instrument and organize industry workshops targeting e.g. software developers, representatives of the glazing industry or building façade planners.

4.2 Contract Research, Exploitation and Commercialization

The following routes towards exploitation and commercialization have been identified:

- co-operation with software companies that develop building simulation software or databases of building envelope components
- existing and new partnerships with rating / manufacturer associations (NFRC, AERC/WCMA, ES-SO, AFRC, BMAA) in order to link their data bases to the metabase
- contract research for glazing and shading product development applying the developed methods
- characterization services for innovative products with beneficial properties that can be demonstrated only by applying the sophisticated methods developed within the project
- review and validation of in-house tools that building envelope product manufacturers have developed for their own use
- steps taken: presentation of ICON results and activities at conferences and IEA, NFRC, AERC, ES-SO and ICG-TC10 meetings; ES-SO-hosted webinar to disseminate ICON results to its members in conjunction with the final ICON meeting

Related customers/customer segments for research and development include:

- software development companies addressing building simulation and associated product data bases
- large architectural and construction companies
- building envelope component manufacturers

Related marketing activities (carried out/envisaged/planned) include:

- presentations at meetings of manufacturers' associations (ongoing)
- presentations/stands at trade exhibitions addressing construction, building product and building planning professionals (envisaged – hampered by the corona pandemic)
- communications via Internet platforms, press releases, fliers (ongoing)

So far, the ICON team has taken the following steps to initiate follow-up research and development projects (public and private sector):

- research project sketch to "Improve the Quality and Cost-Benefit Ratio of Building Envelopes by Providing Product Data Efficiently and Using it in Software to Support their Planning" (EQWIN-P) submitted to the German Federal Ministry for Economic Affairs and Climate Action (BMWK)
- Summary of Request for Proposal (RFP) on "NFRC recognition of laboratory SHGC determination using a solar simulator in accordance with ISO 19467" presented and approved at NFRC Fall Meeting in 2021; presentation of full RFP scheduled for NFRC Spring Meeting in 2022

The impact on each organization's development (e.g. within the business fields of the involved Fraunhofer Institute(s)) includes:

- expansion of BIM-compatible services to complement existing simulation and measurement services

The following aspects of the common marketing strategy were presented in the original Collaboration Plan:

New sources of revenue

- RDA work will provide a new source of revenue from industrial data submitters, who pay a fee for each data set submitted
- Glazing and shading manufacturers will commission measurements to supply the accurate and detailed data needed as input for the new data base, component models and building-level simulation programs
- Component manufacturers will commission joint component development, based on the new modelling and measurement capabilities developed in ICON

- Building planners will commission studies to determine the relative effect of sophisticated daylighting and/or energy-saving building-envelope components in specific buildings, knowing that they will be accurately evaluated
- Major funding agencies, such as US DOE, California Energy Commission, etc. will potentially provide additional funding for related projects, based on joint research work and clearly identified research gaps, resulting from this project.

Each of these points is still valid. However, it is anticipated that RDA revenue for Fraunhofer ISE will be lower than originally projected, as purely administrative-type activities have been removed from the scope, as described in more detail in the Section on WP3.

Dissemination strategies from the original marketing strategy:

- The status of Fraunhofer ISE as an RDA for new and existing data bases will document its close collaboration with LBNL and be publicized by joint publications in trade journals and joint presentations at industrial associations
- The web-accessible cloud-based IGSDB will be accessible free of charge via glazing and shading manufacturers' websites and through window and window attachment rating organizations
- Publicized open-source calculation engine will be promoted through interactions with industry and through joint publications
- LBNL and Fraunhofer ISE will mutually refer to each other's capabilities, as appropriate, when addressing industrial partners

These points are also still valid.

Ideas have been discussed during the course of the ICON work for a business plan to ensure continuation of the metabase after the end of the ICON project. Through partnerships with manufacturers and AEC companies, we envision the metabase becoming a widely used resource for providing accurate and data-rich information for better design of energy-efficient and sustainable buildings.

A significant number of the applications corresponding to transferred research results that were listed above already include or directly lead to contract research, exploitation and commercialization. These include:

- Access to the IGSDB (North American database of glazing and shading products) via a defined API and implementation of the metabase API will promote its use within the glazing and shading industries. Combined with the establishment of RDAs in both North America and Europe, increased interest in populating this data base will generate revenue through RDA work.
- Improved procedures to characterize thick, light-scattering glazing layers by measurement and calculation will be exploited as a service provided by both partners and be a selling point for research projects to develop new complex fenestration components and systems

- Similarly, access by the partners to improved procedures within the RADIANCE ray-tracing program to process BSDF data has already proven to be an advantage in acquiring research contracts from manufacturers interested in developing and validating their own proprietary software to demonstrate the daylighting or energy-saving features of their specific complex fenestrations systems.
- Inclusion of databases and software tools into the rating and certification process of NFRC, AERC, ES-SO, and WinCover. This will lead to an increased market reach of energy-efficient products and will provide a steady revenue stream for the continuing updates and maintenance of these resources. The ability to update and maintain databases and software tools beyond the duration of a research project has proven to be critical to maintain relevance and justify investment. A negative example is provided by the EU-funded WinDAT project, where initial funding was provided for the data base establishment and initial population with glazing and shading, but no provision was made for financing long-term maintenance, and which has almost become redundant because the data refers to many products that are no longer commercially available. A powerful, positive example for success due to a clear plan for post-project lifetime is provided by the North American IGDB, with established industry support and continuing success more than 30 years later.

One clear challenge continues to be the complexity of trans-Atlantic legal negotiations. However, the experience gained in initially setting up this ICON project, and also in establishing Fraunhofer ISE as the European RDA for NFRC, should be helpful as a starting point for future commercial forms of collaboration which need a legal framework.

5 Outlook: Roadmap for the next stage

Regarding the network of product databases of WP2, the next stage could be a project to demonstrate the advantages for the stakeholders. The concept of methods and approvals could be developed further. For the methods, it would be helpful that data refers in detail to the method which was used to create it. Especially the idea of “methods as a service” can be helpful in the long term because it facilitates the decision by many institutions to use the same method. The management of users and access rights should further be developed, too. Databases shall be able to determine which data they return to which institutions. The network should be developed in a way that it becomes attractive for manufacturers to provide data in this way and that it becomes easy to use the data as a planner. Therefore, it is important to help software companies to extend their applications so that they can use the network of databases. Fraunhofer ISE and Fraunhofer IBP have collaborated, with the support of LBNL and various glazing, solar-shading and building software companies, to submit a project application (EQWIN-P) to the German Federal Ministry for Economic Affairs and Climate Action (BMWK) to meet these goals.

Currently, the network of databases focuses on optical data about glass panes. It would be good to increase the amount of high-quality data about shading. The databases could also store data about “units” like a glazing with frame. The data schema could also be extended to other domains like hygrothermal data or data about life-cycle analysis. The network could be extended in the long-term from building envelopes to building products in general. GAIA-X could be a suitable framework for such a wide interaction between product data of components and Building Information Models (BIM).

Efforts will continue after completion of the ICON project to create a web portal for the submission and management of glazing and shading records for the IGSDB, for easier maintenance and communication followed by the official release of IGSDB for general user and RDA use for all glazing and shading products. Specifically, the next steps are to

- Implement the enhanced IGSDB with integrated data checking, viewing and peer review functionalities and release fully tested version for production use
- Complete release version of WINDOW 8
- Develop committee drafts (CD) and draft international standards (DIS) for updated windows and shading standards
- Expand both NFRC and AERC RDA in North America and Europe and increase number of records for both glazing and shading

As a result of WP2, a cloud-based, BIM-compatible, internationally recognized BSDF database portal is available. The metabase will facilitate querying and access to child databases hosted by research institutions, manufacturers, and other sources worldwide. Certification of data would be left to the discretion of providers of child databases. At present there are no maintained, comprehensive libraries of shading and daylighting products for detailed daylighting or glare analyses of fenestration systems. LBNL efforts in this direction are limited to low-resolution (i.e., Klems) BSDF data. Methods for generating BSDF data for different applications are relatively new and are anticipated to evolve as measurement procedures, simulation tools, and daylight metrics improve. In this process, at least the following key issues should be considered:

1) Adequate metadata (i.e., documentation) will be critical for maintaining a transparent database that can be updated and improved incrementally. Documentation will need to include not only methods used to measure the material or fenestration system, but also the tools used to process the raw measured data to its final BSDF tabular form (e.g., software version, interpolant settings), references to empirical validation of methods, and other salient information needed to evaluate the sufficiency and accuracy of the library entry.

2) The range of simulation activities conducted by industry spans a broad range of purposes: a BSDF library could include non-certified entries generated for unique architectural projects and certified entries for manufactured products generated using approved, standardized methods. As building certification programs and standards start to incorporate comfort and health into their metrics, the latter may be needed prior to final specification and approvals. Labeling and certification procedures indicating intended use of the data would be needed to differentiate between the various types of entries. Procedures for ensuring compliance with standards in the data submission process and renewal of certifications would need to be worked out amongst shading and daylighting manufacturer organizations (e.g., AERC, ES-SO) on a global scale.

3) For some systems, particularly those with specular transmission or reflection, “high resolution” data (e.g., tensor tree k=6) could be generated erroneously from library entries that have inadequate underlying models and/or raw data, leading to unintended errors. To qualify library entries, metrics are required to provide an effective, achievable resolution value based on the raw data and simulation settings used to generate the data driven BSDF. Alternatively, preemptive tools could be used to prevent generation of tabular BSDFs if the underlying data are of insufficient angular resolution.

4) To find materials or single layer shade system data in the library that meet specified criteria, BSDF-specific metrics will need to be defined so that innovative daylighting products can be located by consumers when the database is queried. These metrics will need to be defined carefully to avoid unintentional exclusion of products from consideration on a proposed project. The new metric developed in WP4, direct-conical transmittance, could be considered for use by experts as part of this process.

The RDA framework which was created during the ICON project will ensure continuing collaboration between LBNL and Fraunhofer ISE, not only at the practical data submission level but also in the joint development and testing of the RDA tools accompanying the full roll-out of IGSDB submission processes. In future, the determination of glazing optical properties from IGSDB data according to European standards could be added as a further feature with which Fraunhofer ISE, as the European RDA, could support European glazing and shading manufacturers.

A proposal to NFRC to support collaboration between LBNL and Fraunhofer ISE on the topic of indoor SHGC measurement applying a solar simulator is currently being prepared. The initial request was already approved by the NFRC Technical Committee at its Fall Meeting in 2021; the full Request for Proposal is to be presented at the NFRC Spring Meeting in 2022.

At a more general level, both LBNL and Fraunhofer ISE intend to continue the practice that has started within the ICON project of mutual recommendation to potential industrial customers from continent of the partner (i.e. LBNL for North America, Fraunhofer ISE for Europe). Where possible, both ICON partners would be willing to co-operate with each other on work contracted by industrial companies. With the experience gained during the ICON project in Trans-Atlantic legal negotiations, this should be more feasible than during the ICON project application phase, but the legal hurdle for such co-operation is still quite high.

Collaboration on joint scientific papers can be expected to continue on an ad hoc basis. Deliberate simultaneous participation in suitable IEA Tasks could be one method to facilitate this.

Another vehicle for continued collaboration could be the establishment of a new WG within TC163 and work on updating ISO standards for thermal and optical characterization of windows and shading systems.

6 Comments of the project leaders

Helen Rose Wilson, Fraunhofer ISE: It has been exciting to experience how the cooperation within WP2 has intensified fruitfully, resulting in both a detailed structure and operational implementation of the metabase and also provision of a new API to enable communication with the IGSDB. The participants of WP1 and WP4, who have a longer history of collaboration, have effectively built on each other's contributions to implement an efficient workflow to measure and process the BSDF data needed for glare-protection evaluation of textile blinds. This includes an improved procedure for interpolating data within the Radiance ray-tracing environment and a procedure to determine and eliminate the effect of an offset "dark signal" in the photogoniometric measurements. The ILC on diffuse glazing has resulted in provision of specific requirements for their characterization in the relevant NFRC documents. Within WP3, the European RDA status for Fraunhofer ISE was achieved for the IGDB and will serve as a basis for achieving the same status for the IGSDB. The work within WP5 intensified toward the end of the project; there, it will be important to disseminate ICON results jointly as far as the constraints of geographical separation allow.

The framework of the ICON program was certainly of benefit in enabling the project partners to obtain the collaborative results presented in this report. Nevertheless, we must recognize that, in contrast to co-operation within Europe, which is facilitated by EU research programs and a common European legal framework, the external environment is not as favorable to long-term trans-Atlantic co-operation. However, as indicated in Section 5, we have created and identified opportunities to continue to co-operate in the future and intend to make use of them.

In my view, the key success factor for this cooperation is the exhilaration we all feel when we are able to "bounce ideas off each other", mutually benefitting from long-term experience but slightly different perspectives on the subjects addressed, and thus achieving progress which neither partner could have achieved completely on their own. Now we must get the ideas that we have implemented "out into the marketplace".

Charlie Curcija, LBNL: This joint project has fulfilled our expectations of synergistic benefits of collaborative work on challenging problems in achieving effective yet accurate methods and producing useful software tools and databases for the design of energy-efficient buildings. While there was an ongoing challenge to coordinate work across 9 time zones and a recent challenge due to the pandemic, which resulted in converting the planned in-person meetings for the last 1.5 years to a web-based one, we have managed to effectively work together through regular web-based meetings and updates and shared data storage (ownCloud). I am pleased with the results for all major tasks (methodologies, databases and software tools development). I am also pleased that we have successfully connected with other providers of material property databases (Fraunhofer IBP and WUFI material database), with the expressed commitment to extending the metabase beyond optical properties to include thermo-physical properties for easy and effective access by building professionals, academia and consumers.

We met the expectation to complete database implementation and release software tools for external testing, as well as ramp up outreach and publication push so that there is active feedback from users and wider acknowledgement of the resources that will be available from this project. We also expect to continue active coordination with AERC, NFRC, ES-SO and WinCover and to get their buy-in of the final product(s).

7 Literature

References cited in the WP descriptions were provided as footnotes. All publications and papers resulting from the ICON project are listed in the Appendix.

8 Acknowledgements

The ICON team is very grateful to the funding bodies which made this collaborative work possible, the U.S. American Department of Energy for LBNL and the Fraunhofer Society for Fraunhofer ISE. The Principal Investigators thank particularly the ICON coordinator, Meret Krämer, for her constructive and constant support. We are also very grateful to our Scientific Advisors, Stephen Selkowitz and Tilmann Kuhn, for the support and guidance they have provided throughout the project. We sincerely thank our industrial experts for their willingness to provide feedback that ensures that the generated results will be of use to the commercial solar-shading and glazing sectors. Finally, we greatly appreciate the contributions made by the members of the Steering Committee for maintaining links between the project work and the wider context of energy-efficient buildings and related fields addressing the global energy transformation.

Some of the work within WP1 and WP4 benefitted from discussions with the wider daylighting within Subtask C2.2. of the IEA-SHC Task / EBC Annex 77: Integrated Solutions for Daylighting and Electric Lighting, led by David Geisler-Moroder, Bartenbach GmbH, who permitted reproduction of images that he had generated, in Figure 33.

9 Table of Abbreviations

AERC	Attachments Energy Rating Council
AFRC	Australian Fenestration Rating Council
AFM	Atomic Force Microscope
API	application programming interface
ASHRAE	American Society for Heating Refrigerating and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
BBSA	British Blinds and Shutters Association
BIM	Building Information Modelling
BMAA	Blind Manufacturers' Association of Australia
BRDF	Bidirectional Reflectance Distribution Function
BSDF	Bidirectional Scattering Distribution Function
BTDF	Bidirectional Transmittance Distribution Function
CEN	Comité Européen de Normalisation
CF	Complex Fenestration
CGDB	Complex Glazing Data Base
CRADA	Cooperative Research And Development Agreement
DGP	Daylight Glare Probability
DOE	Department of Energy
ES-SDA	European Solar-Shading Database
ES-SO	European Solar-Shading Organisation
EU	European Union
ExCo	Executive Committee (of an IEA Programme)
GUI	Graphical User Interface
ICON	International Cooperation and Networking
IEA	International Energy Agency
IKDB	ICON Knowledge Data Base (former name of the metabase)
IGDB	International Glazing Data Base
ICG	International Commission on Glass
IGSDB	International Glazing and Shading Data Base
ILC	Inter-Laboratory Comparison
ISE	Institute for Solar Energy Systems
ISO	International Standardisation Organisation
LBNL	Lawrence Berkeley National Laboratory
NFRC	National Fenestration Rating Council
PV	Photovoltaic
PVB	polyvinyl butyral
RDA	Regional Data Aggregator
SC	Sub-Committee
SHC	Solar Heating and Cooling
SoW	Statement of Work
TC	Technical Committee
URI	Universal Resource Information
USA	United States of America
WP	Work package

Appendix: Overview of activities and outputs of the collaboration to date

Mobility within the consortium

- Visit by Jacob Jonsson, LBNL to Fraunhofer ISE from 13th to 17th May, 2019 for the kick-off meeting and subsequent in-depth WP discussions.
- Visit by Helen Rose Wilson, Tilmann Kuhn and Christoph Maurer (all from Fraunhofer ISE) to LBNL from 29th July to 2nd August, 2019 for in-depth WP discussions.
- Attendance by Bruno Bueno, Fraunhofer ISE at the IEA-SHC Task 61 Meeting in Gdansk, Poland from 16th to 18th September, 2019
- Visit by Charlie Curcija and Jacob Jonsson, (both LBNL) to Fraunhofer ISE from 17th to 21st February, 2020 for in-depth WP discussions and liaison with ES-SO representatives.
- No further mutual visits were possible due to the travel restrictions introduced in response to the global Covid pandemic.

Thesis work and academic degrees

<u>M.Sc. Thesis (WP1).</u>

- Luis Camilo Londono. Master Thesis for M.Sc. in Renewable Energy Engineering and Management. Evaluation of alternative thermal models for complex fenestration systems. University of Freiburg, 2019.
  Supervisor: Bruno Bueno, Fraunhofer ISE.
  Publications by the LBNL partners on thermal fenestration models formed an important basis for the student's research.

<u>Ph.D. Thesis (WP1).</u>

- Abel Sepulveda. Ongoing Ph.D. studies on the topic of daylighting and building energy prediction tools at the Tallinn University of Technology (TalTech)
  Scientific interaction with the LBNL partners on annual glare risk assessment formed an important basis for the student's research.

Publications in scientific journals

Peer-reviewed journal papers

Sepúlveda, A., Bueno B., Wang T., Wilson H.R.. Benchmark of methods for annual glare risk assessment. Building and environment 201 (2021), ISSN: 0360-1323. DOI: 10.1016/j.buildenv.2021.108006

Ward G.J., Bueno B., Geisler-Moroder D., Grobe L.O., **Jonsson J.C., Lee E.S., Wang T., Wilson H.R.** Daylight Simulation Workflows Incorporating Measured Bidirectional Scattering Distribution Functions. Energy and Buildings 2022 259 (2022) 111890. https://doi.org/10.1016/j.enbuild.2022.111890

Bilokur, M., Jonsson, J.C., "Four-flux radiative transfer model to determine optical performance of the unknown scattering layer in a multilayer glazing sample", to be submitted to Optics Communications

Tan, Y., Peng, J., **Curcija, D.C.**, Gao, J., Hart, R., **Jonsson, J.C.**. 2020. Parametric Study of Venetian Blinds for Energy Performance Evaluation in Residential Buildings. Energy Journal May 2020. https://doi.org/10.1016/j.energy.2021.122266

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Public relations

High-level, jointly prepared presentation to glazing and solar-shading industrial associations in Europe and the U.S.A. of the ongoing collaborative ICON work and related synergistic work, including measurement procedures and data formats for light-scattering materials. The topics were presented by Fraunhofer ISE to ICG-TC10 and the Bundesverband Flachglas, by LBNL to NFRC and ASHRAE, and by both partners jointly to ES-SO and AERC during the course of the ICON project.

- ICG-TC10 (International Commission on Glass – Tech. Comm. 10) meetings,
- Bundesverband Flachglas (BF - German Architectural Glazing Association),
- NFRC (National Fenestration Rating Council in North America) meetings,
- ASHRAE (American Society for Heating Refrigerating and Air-Conditioning Engineers) TC 4.5 Fenestration meetings
- ES-SO (European Solar-Shading Organisation)
- AERC (Attachments Energy Rating Council in the USA)

ICON project website:
https://www.ise.fraunhofer.de/en/research-projects/icon-lbnl-fraunhofer-ise.html

H.R. Wilson, B. Bueno, C. Maurer, presentations in webinar with LBNL participation on “A booster for solar shading in buildings – new approaches to determine, use and access optical and thermal data” hosted by ES-SO to disseminate ICON results to the solar-shading industry, 23.02.2022, online:

- Optical and thermal characteristics of solar shading and how they can be measured/determined

- Applying software to evaluate the effect of solar shading on energy consumption, daylighting and glare in buildings
- Product data in the cloud – the next step for manufacturers, software companies and planners

After the completion of the final report, LBNL plans to conduct a formal presentation to AERC and NFRC membership, with Fraunhofer ISE participation, about the results from the collaborative and related synergistic work.

ASHRAE and its European equivalent REHVA could be suitable platforms for further dissemination of ICON results to professionals from the Heating, Refrigeration, Ventilation and Air-Conditioning community.

Participation in conferences/ meetings/ seminars/ trade fairs

J.C. Jonsson, Presentation on NFRC Diffuse Glazing Task Group, NFRC Spring Meeting, March 2018, also extended and presented by **H.R. Wilson** to ICG-TC10 spring meeting 2018, 27.4.2018, Venice.

J.C. Jonsson, Presentation on NFRC Diffuse Glazing Task Group, NFRC Spring Meeting, March 2019, also extended and presented by **H.R. Wilson** to ICG-TC10 spring meeting 2019, 12.4.2019, Venice.

B. Bueno, A. Sepúlveda. A specific building simulation tool for the design and evaluation of innovative fenestration systems and their control. IBPSA Building Simulation Conference, Rome 2-4 September, 2019.

J. C. Kohler, P. Lyons, R. G. Hart, **D. C. Curcija**, A Comparison Of The Latest Window Modeling Methods In EnergyPlus. IBPSA Building Simulation Conference, Rome 2-4 September, 2019.

J.C. Jonsson, Presentation on Update on diffuse glazing ILC, NFRC Fall Meeting, October 2019, also extended and presented by **H.R. Wilson** to ICG-TC10 autumn meeting 2019, 27.10.2019, Würzburg.

H.R. Wilson, C. Curcija, Presentation on ICON project, presented by H.R. Wilson to ICG-TC10 autumn meeting 2019, 27.10.2019, Würzburg

H.R. Wilson, C. Curcija, Presentation on ICON project, presented by H.R. Wilson to Bundesverband Flachglas, Pro Glas meeting, Troisdorf, 3.12.2019 (mediated by industry expert M. Elstner, AGC Interpane)

D.C. Curcija, J.Q. Peng, H. Goudey. 2019. “Energy Savings from PV-Integrated Window Glazing”. Thermal Performance of Building Envelopes XIV, Clearwater Beach, Fl. December, 2019

Curcija, D.C., Hart, R.G, Goudey, H. 2019. “Experimental Setup for the Measurement of Detailed Heat Transfer in Window Attachments”. Thermal Performance of Building Envelopes XIV, Clearwater Beach, Fl. December, 2019

B. Bueno, E.S. Lee, T. Wang. Participation in online meetings of IEA-SHC Task 61 “Solutions for Daylighting and Electric Lighting” during 2020 and 2021.

J.C. Jonsson, Presentation on Update on diffuse glazing ILC, NFRC Fall Meeting, October 2020, also extended and presented by **H.R. Wilson** to ICG-TC10 autumn meeting 2020, 23.10.2020, online.

H.R. Wilson, D.C. Curcija, J.C. Jonsson, “Fraunhofer ISE as the European Technical RDA for NFRC“, presented by H.R. Wilson to ICG-TC10 autumn meeting 2020, 23.10.2020, online.

D.C. Curcija, “Energy Performance of Window Shading“. Presentation at ASHRAE Virtual Winter Conference, February 2021.

Geisler-Moroder, D., **Ward, G.J., Wang, T., Lee, E.S.**, 2021. “Peak extraction in daylight simulations using BSDF data”. Proceedings of Building Simulation 2021 Conference, International Building Performance Simulation Association, Bruges, September 1-3, 2021

Bueno B., Sepúlveda A., Maurer C., Wacker S., Wang T., Kuhn T.E., Wilson H.R.. “Easy-to-Implement Simulation Strategies for Annual Glare Risk Assessments based on the European Daylighting Standard EN 17037”. Proceedings of Building Simulation 2021, International Building Performance Simulation Association, Bruges, September 1-3, 2021

Maurer, C., Wacker, S., Bueno, B., Jonsson, J.C., Lamy, H., Bush, D., Shi, M., Sprenger, W., **Mitchell, R., Wilson, H.R., Curcija, D.C., Kuhn, T.E.** “Optical and Calorimetric Product Data in Building Information Modelling”. Proceedings of Building Simulation 2021, International Building Performance Simulation Association, Bruges, September 1-3, 2021

J.C. Jonsson, Final presentation on diffuse glazing ILC, NFRC Fall Meeting, October 2021, also extended and presented by **H.R. Wilson** to ICG-TC10 autumn meeting 2021, 01.10.2021, online.

H.R. Wilson, C. Maurer, “Project EQWIN-P”, presented by H.R. Wilson to ICG-TC10 autumn meeting 2021, 01.10.2021, online.

Burns, E., Phan-Gruber, E., Rivett, B., Hart, R., & **Curcija, C**. 2018. New Rating Opening Windows to a World of Comfort, Opportunity, and Cost-Effective Savings. Lawrence Berkeley National Laboratory. http://dx.doi.org/10.20357/B7B88V

Peng,J., **Jonsson,J.**, Hart, R., **Curcija, D.C.**, Selkowitz, S.E. 2017. “Parametric study of window attachment impacts on building heating/cooling energy consumption.” *Proceedings of the 15th IBPSA Conference*. San Francisco, CA, USA, Aug. 7-9, 2017.

Kohler, C., Lyons, P., Hart, R.G., **Curcija, D.C**. 2019. “A Comparison of the Latest Window Modeling Methods in EnergyPlus.” *16th IBPSAS International Conference and Exhibition*. 2-4 September, 2019. Rome, Italy.

Targeted projects in the public and private sector

Public projects

A publicly funded project for the ICON consortium is improbable due to the lack of funding bodies for trans-Atlantic co-operation.

The proposal for a joint NFRC research project on indoor SHGC measurement using a solar simulator is being prepared.

Fraunhofer ISE and Fraunhofer IBP, with the support of LBNL, have submitted a proposal for a German national project, EQWIN-P, to extend and maintain the metabase developed in WP2 and supporting activities.

Development of the next generation of WINDOW and THERM (version 8) software tools are funded by the US Department of Energy (DOE), as a continuation of multi-decade development efforts to provide accurate and accepted tools used globally by tens of thousands of users, from manufacturers to certification agencies, academia and other researchers. Part of the overall development of these tools is gradual open sourcing and modularizing of calculation engines and connection to IGSDB and IKDB. As a result of this effort, WinCalc calculation engine for WINDOW has been integrated into the WINDOW tool. This engine has been described earlier and is available as open source code. The new Finite Element Method (FEM) engine HygroThermFEM has been developed for THERM that now enables THERM to perform dynamic modelling (addition of time domain) and moisture modelling. Beta version of WINDOW 8 and THERM 8, along with open source code is available on the LBNL windows software development website.

Under the funding from DOE, additional window shading systems models have been developed during the ICON project, covering roller shutters and window quilts, as well as window awnings, in addition to previously developed models for 7 shading and other window attachment systems. These models are incorporated into the WINDOW and AERCalc tools and AERC currently provides certification for these products. LBNL had conducted software training for AERC certified simulators and conducted exam to approve certified simulators.

Industry projects

The metabase still needs to be developed further to make it accessible to commercial companies, which is the reason for submitting the EQWIN-P project application mentioned above. If successful, it will involve numerous companies from relevant branches, who in turn can be expected to commission smaller industrial projects specific to their own needs and applications.

Fraunhofer ISE has offered to support ES-SO and the BMAA to implement the ICON API and to participate in the interaction with the metabase. BMAA has asked specifically whether Fraunhofer ISE could provide measurements that are needed to populate its new data base.

As the NFRC falls within the scope of an “industrial customer” in the Fraunhofer context, the contract between NFRC and the Fraunhofer-Gesellschaft for RDA work by Fraunhofer ISE counts as an “industry project”.

The ICON team is currently also preparing a “Request for Proposal” (RFP = “call for quotes”) to NFRC which aims to introduce an indoor method to determine the Solar Heat Gain Coefficient (SHGC), which is based on ISO 19467, into the NFRC framework. This would widen the options to glazing manufacturers to determine the SHGC, a characteristic that is increasingly demanded for building-energy rating and building approvals.

Many small industry projects benefit from the positive image created by the collaboration between LBNL and ISE within ICON. In particular, R&D projects applying the programs that were further developed in WP1 and/or using measured data of the type validated in WP4 have already been contracted and more can be expected in future. However, to respect the confidentiality of the contracting companies, they are not described in greater detail here.

LBNL continues to work closely with NFRC and AERC organizations and provides continued software support for THERM, WINDOW and AERCalc. New versions of approved software tools WINDOW 7.8, THERM 7.8, and AERCalc 1.3 are posted on LBNL software download website.

Licenses

Open-source licenses exist for the following software tools:

- WinCalc
- PyWinCalc
- Radiance peak-extraction extension
- Frads (automation of Radiance workflows)
- HygroThermFEA

Licenses are held by the Trustees of the University of California for download and use of the following software tools:

- WINDOW
- THERM
- AERCalc