Thermal modelling of complex fenestration systems – Comparison of a BSDF-based model with simplified approaches

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Abstract

In this paper the theoretical concept of modelling complex fenestration systems is shown firstly by the development of two simplified modelling approaches and secondly by a newly developed model in TRNSYS17 based on BSDF-data and the ISO15099 standard.
Final results of a comparison between the more detailed BSDF model and the simplified models based on the bi-directional SHGC will be worked out and described. By simulating two different blind systems incorporated in the façade of a standard office room (Fig. 1), the capabilities and restrictions of the simplified approaches in modelling conventional, diffuse shading blinds and daylight deflecting, specular blinds are shown.
Depending on the external boundary conditions and pre-defined settings to be done for the simplified model approaches by parameter studies, the results show satisfying correlations between all models for static and dynamic boundary conditions.

1. Introduction

The use of complex fenestration systems (CFS) offers a high potential in energy savings compared to the state of the art shading systems mainly installed in the commercial building stock. Especially for office buildings, light-redirecting systems allow an improvement of both, visual and thermal comfort (Fig. 1). Former research work showed a significant potential in reduction of artificial lighting due to higher workplace luminance by daylighting (Hauer et al. 2011). Furthermore a reduced solar gain in summer season through transparent facades and energy efficient shading control leads in a significant reduction of the cooling energy demand.

To account for these requirements in the building design, a detailed numerical method for a coupled thermal and lighting simulation of complex façade with integrated daylight deflecting (specular) systems in TRNSYS and RADIANCE is worked out on the national research project lightSIMheat, funded by the Austrian Research Agency (FFG).

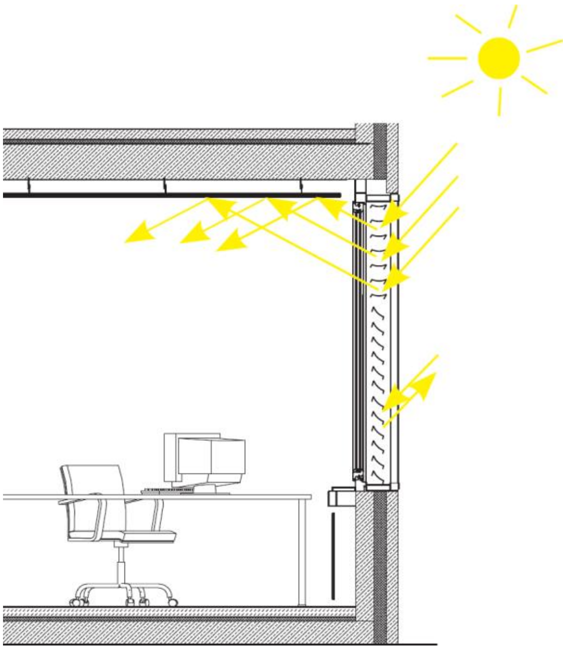

Fig. 1 – Light redirecting facade system

For the thermal evaluation of such a complex façade, simplified approaches based on a two-dimensional solar heat gain coefficient are worked out.
Originally intended as a first possibility to implement complex glazing systems in TRNSYS, ongoing developments in the field of thermal modelling of CFS are based on the use of bi-directional-scattering distribution functions (BSDFs).

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Although simulation models for CFS based on BSDF-data enables high accuracy in modeling purposes, an extensive amount of input data as well as a high level in specific user expertise for the time-consuming data pre-processing is necessary. Besides them, detailed product specification of every single component of the system (glazing, blind…) is necessary for the overall setup.
In contrast to the BSDF-model, the idea behind the simplified approaches is to use the angular dependent g-value instead of the comprehensive BSDF dataset to characterize the thermal properties of the CFS.
In this paper, a comparison of these simplified modeling approaches with the more detailed BSDF-model is presented. Besides a conventional façade system with an outside raffstore, further investigations are made for a specular (daylight deflecting) blind system. Optical BSDF data are generated by external ray-tracing and used in WINDOW7 to set up an overall system including the glazing.

2. Modelling of CFS

Compared to conventional glazing systems, CFS including a shading layer (venetian blinds, screens or woven shades) shows a bidirectional scattering of the radiation striking the shading layer.
Due to the high flexibility of the system, the setup of CFS and the interconnection of the occurring physical phenomena, (e.g. radiative heat exchange, natural or forcing convection, conduction) and the modelling of optical and thermal properties of such a system is very complex. Furthermore, blind surface properties (diffuse reflective or specular reflection) as well as their geometry (planar, curved, or multi-curved) extend the variations in modelling purposes.
In former releases of TRNSYS Type56 (Multizone-building model) the amount of shaded solar fraction was treated as blocked sun radiation by a flexible shading factor (Fc-factor). Internal radiation exchanges between glazing and blinds and between blinds themselves were possible to model by fixed values to describe the radiative interaction approximately.
As these processes are dynamically and strongly affected by the real system setting, the calculation procedure was extended to calculate the absorbed solar radiation in the different layers describing the energy demand and comfort situation in the room behind in more detail. By developing simplified approaches, first investigations were undertaken in an improved modelling of glazing systems incorporating venetian blinds. At the same time decreasing the high efforts of modelling and detailed product data for simulation input, major simplifications were realized.

2.1 Simplified approaches

For glazing systems without shading devices a solar heat gain coefficient (SHGC) one-dimensional dependent from the incident beam radiation is sufficient for exact calculations (standard window model in TRNSYS). However, for an accurate modelling of complex glazing system including blinds, the SHGC has to be defined in a bi-directional dependency of the incoming solar radiation by the azimuth- θ and zenith angle γ.
By this fact and based on the standard window model in TRNSYS, two methods were implemented to improve the thermal modelling of complex fenestration systems:

- g- model
- Abs- model

Both methods calculate out of pre-calculated datasets with values for transmission, absorption and SHGC, depending on the solar azimuth and zenith angle separately, for beam and diffuse radiation the solar energy passing the CFS. The calculations for the diffuse radiation part is additionally divided into sky- and ground diffuse radiation. Different slat angles as well as changes of the blind position during the simulation can be taken into consideration.
The calculation of the passing energy is executed “externally” from the building model and further linked as input into the multizone-building model (Type 56) in TRNSYS. The calculations are done for each time step and split up into both the physical

parts of the SHGC - transmission and secondary heat flux (Fig. 2).
The former is treated as fully radiative internal gain and is directly connected to the zone air node. The second is treated as wall gain representing the thermal radiation part of the passing energy and is in exchange by longwave radiation and convection with the zone air node. For a correct representation of the thermal losses/wins (u-value) within the zone model, the internal window model in Type56 has to be defined corresponding to the system glazing, but in a fully shaded situation (Fc = 1).

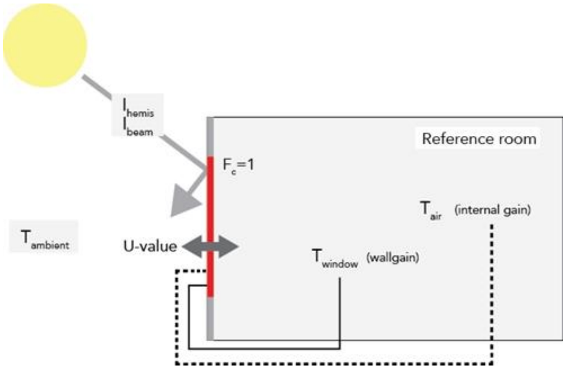

Fig. 2 – Integration of the simplified approach via internal gain and wall gain in the multizone-building (Type56)

In the *g-model* the solar radiation through the transparent façade area is calculated – like the naming - by the pre-calculated overall SHGC (or g-value). The separation into transmission and secondary heat flux (internal gain / wall gain) is done by a constant ratio between transmission and secondary heat flux over the yearly trend. The factor has to be defined for each system separately in advance and varies slightly with glazing type and tilt angle of the blind.
The *Abs-model* allows the implementation of absorption- (angle dependent) and emission coefficients for glass panes and blinds (fixed). This enables a more accurate modelling of the longwave radiation exchange in between the layers. Both models do not include detailed effects of IR-transparency, longwave radiation in slat cavities by view-factors and detailed convective behaviour between and around the blind layer.

2.2 BSDF-model

For a detailed modelling of CFS within dynamic thermal simulation tools, the latest research models based on bi-directional scattering distribution functions (BSDF) are available (Hiller und Schöttl 2014).
The modelling method is separated into shortwave radiation modelling by the pre-calculated BSDF data and the longwave radiation modelling according to algorithms defined in the ISO15099 standard as the current most comprehensive modelling standard for blind systems (Norm ISO 15099:2003).
Based on the established concept of a layer-by-layer calculation for glazing systems, the ISO15099 standard is an enhancement of this method to be also adaptable for CFS (Fig. 3). It specifies detailed calculation procedures determining the optical and thermal properties of shading layer by a discretized blind model as well as the convective behavior by a comprehensive pressure drop model.

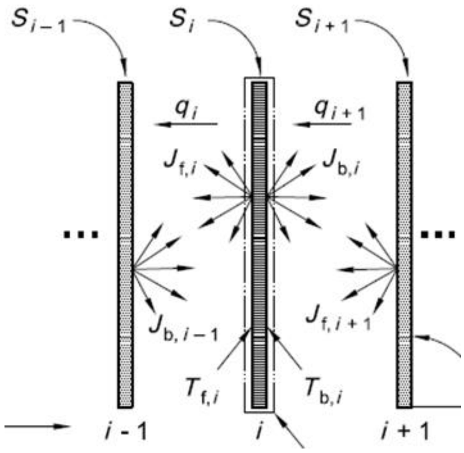

Fig. 3 – Layer-by-layer modelling according to ISO15099

Both transmitted solar radiation depending on geometry and optical surface properties as well as the thermal driven radiosity balance depending on solar-thermal properties are calculated in detail by the view-factor method and determine the overall energy transmittance of the CFS. Therefore as a main contrast to the simplified *g-model*, the BSDF model calculated the SHGC instead of using it as a pre-calculated input, while the *Abs-model* is positioned in between both concerning modelling accuracy. The BSDF model in TRNSYS implies the detailed thermal model according to Fig. 3. The calculation of the optical properties is fully adapted by the integration of external BSDF data.

This method was introduced by (Klems 1994) and describes a flexible method to calculate the bi-directional solar transmission of a CFS by simple matrix multiplications. In discretizing the hemisphere at the front and the back side of the CFS-layer into 145 areas (Klems-patches), a detailed specification of the optical properties of each layer depending on azimuth and zenith angle is possible.

The resulting data matrix contains in its standard resolution 145 outgoing values in overall transmission and reflection of the CFS for each of the 145 incoming values on the CFS. This dataset is defined as BSDF and covers the optical blind modelling for the full hemisphere at the front and back of the complex glazing (Fig. 4).

$$\tau = \frac{I_{out}(\theta_{out}, \gamma_{out})}{I_{in}(\theta_{in}, \gamma_{in})} \quad (1)$$

Furthermore, the new implemented BSDF model in TRNSYS has a modular structure, which allows, in combination with the well-established software tool WINDOW7 from LBNL, a flexible implementation of different glazing systems including blinds. For all different slat angle positions needed in the simulation, a separate BSDF dataset has to be pre-generated. Also changing system properties (blind geometry, optical surface properties…) used in one simulation needs to be provided by separate BSDF datasets.

In previous research work, static validations of the new BSDF model with WINDOW7 as well as quasi-dynamic validations with the implemented BSDF model of EnergyPlus8.0 by comparative simulations under varying system parameters were presented.

The new BSDF model shows excellent accordance with WINDOW7 results under static conditions. The model comparison with EnergyPlus8.0 shows slight deviations, which mainly result from general modelling differences between TRNSYS and EnergyPlus as well as existing limits in EnergyPlus for setting steady boundary conditions.

Detailed analyses and results of the undergone model validations are described in published work by (Hiller und Schöttl 2014) and (Hauer et al. 2014).

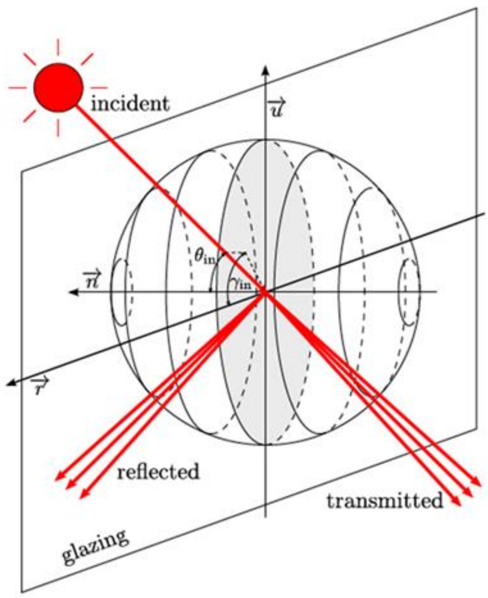

Fig. 4 – Optical modelling with BSDF data

3. Simulation setup and variants

3.1 Reference room

For the comparison of the simplified approaches against the detailed BSDF model, two blind systems are investigated. For the simulations of an exemplary office, a reference room with standard interior design and geometrical dimensions according to Fig. 5 is defined.

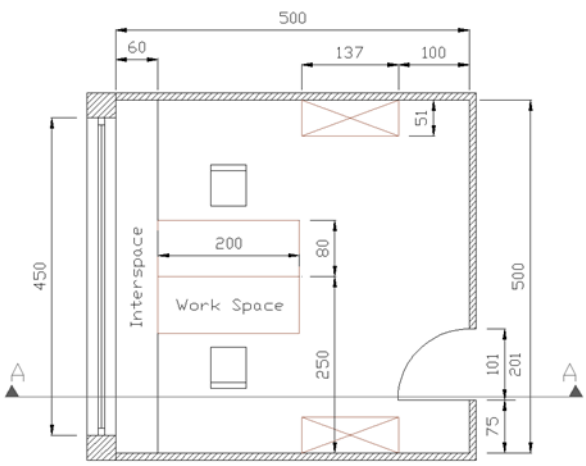

Fig. 5 – Dimensions of the double-office reference room

All walls are modelled as boundary walls except the external south façade including the window.

The façade consists of a parapet for technical equipment and a large window area, which offers all opportunities for an advanced daylighting system.

Table 5 – Boundary definition for the reference room

Definitions – Reference room	
Climate	Graz, Austria
U-value wall	0,15 W/m²K
U-value window	0,8 W/m²K
Window surface	9m² (w: 4,5m / h: 2m)

Profiles for internal gains, operating hours, heating/cooling and air change rate are defined according to SIA 2024 standard.

3.2 Systems

The comparative simulations are undertaken for a conventional (diffuse) outside raffstore (Fig. 6) and an in-between specular (re-directing) blind system "Alar Lamella" (Fig. 7).

WINDOW7 as a well-established software tool, developed and regularly updated by the LBNL, and is used for the input data pre-processing for the BSDF model according to the layer specifications in Table 6 and Table 7. The product data for the glazing and the gas layers are imported from the included database (IGDB). The shading layers are BSDF datasets, generated with the RADIANCE program genBSDF (Geisler-Moroder 2011).

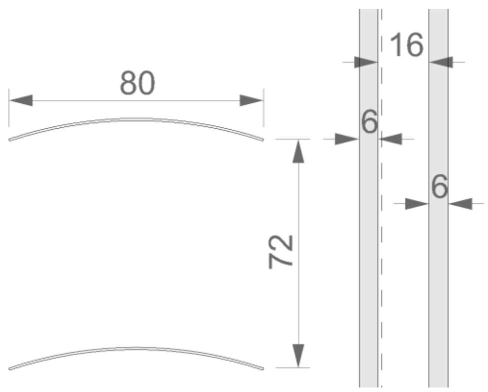

Fig. 6 – Geometrical definition [mm] - external raffstore „RAF"

Table 6: layer definition - external raffstore

ID	external raffstore (Raf)	[mm]
	BSDF (Raffstore – 45deg)	56.5
1	Gas 1 (Air)	43.5
7111	Glazing 1 (ip_ipl6E.ipe)	6.0
2	Gas 2 (Argon, 100%)	16.0
7199	Glazing 2 (ip_fl_6.ipe)	6.0

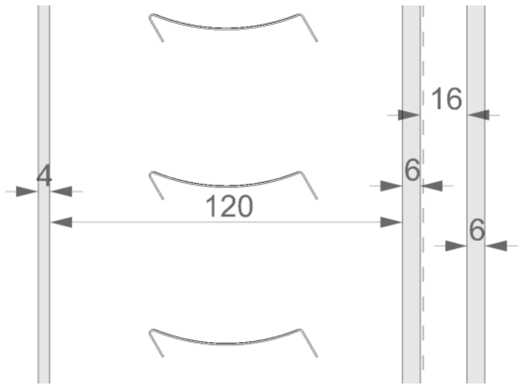

Fig. 7 – Geometrical definition [mm] spec. in-between blind „Alar"

Table 7: layer definition - specular in-between blind

ID	Alar Lamella (Alar)	[mm]
7197	Glazing 1 (if_fl_4.ipe)	4.0
1	Gas 1 (Air)	33.5
	BSDF (Alar_SUN – 45deg)	53.0
2	Gas 2 (Air, 100%)	33.5
7111	Glazing 2 (ip_ipl6E.ipe)	6.0
	Gas 3 (Argon 100%)	16.0
7199	Glazing 2 (ip_fl_6.ipe)	6.0

The input data for the simplified approaches are provided as pre-calculated datasets separately for the beam- and diffuse components of:

- Solar transmission (overall system)
- Bi-directional SHGC (overall system)
- Absorption coefficients (for each layer)

The matrix for the beam components implies values in 5°-intervals for the azimuth range (0-360°) and the zenith range (0-90°) of the whole hemisphere, which ends up in a 73x19 matrix for each component and slat angle. The data set for the diffuse components consists of three separate values for the sky, hemisphere and ground part for each slat position.

The main difference between the BSDF model and the simplified approaches is therefore defined in the different dataset structure and the method of different modelling as mentioned in 2.1.

3.3 Simulation variants and boundaries

3.4 Static simulation

In a first step, stationary calculations are realized by simulating the reference room (3.1) as full adiabatic with a sun-exposed window including the blind system with a slat angle of 45°. Internal gains are neglected for the static case and quasi-static case.

Table 8 – Conditions for static simulation

Boundaries – static simulation	
$T_{amb}/T_{sky}/T_{grd}$	20°C
I_{Sol}	783 W/m²
AI	Var.1: 0° / Var.2: 45°
Heating/ Cooling	20°C

Due to this fixed simulation conditions the resulting SHGC can be calculated by the cooling load and the incident radiation on the window:

$$SHGC = \frac{Q_{Cool}}{I_{window} * Area} \quad (1)$$

3.5 Quasi-static simulation

For the quasi-static calculations, the reference room is again modelled fully adiabatic with constant outside boundary temperatures according Table 8. The incident radiation and sun angle are dynamic and read in from the climate data (Location: Graz).
The simulation was now undertaken for both systems with all models in a yearly term. The modelling accuracy is shown by the resulting cooling load for three different slat positions.
Furthermore resulting room temperatures as well as glazing temperatures are analyzed as graphs based on hourly values. A week in February (01. – 07.) representing winter conditions and a period in July (01. – 07.) representing summer conditions were used as examples.

3.6 Dynamic simulation

In a final stage the simplified approaches were compared with the BSDF model under fully dynamic conditions in the simulation. The simulations are done for both systems again over a year including all definitions concerning reference room and the internal loads from 3.1.

4. Results

4.1 Static results

The results for both systems and both incident radiation scenarios are shown in Table 9 / Table 10.
The results are presented as absolute values for each model and the relative deviation in relation to the BSDF model results, as this is assumed to be the most accurate one.
In general, the results for the external raffstore have a better accordance with the BSDF model for the perpendicular radiation. For the tilted radiation the absolute values decreases, which leads to higher relative deviations although the absolute values are still in the range.

Table 9 – Stationary results of SHGC for the external raffstore

SHGC (I_{sol} = 783W/m² , γ_S = 90°, θ_S = 0°, AI = 0°)				
Slat angle		**0°**	**45°**	**75°**
BSDF		0.482	0.168	0.021
G	abs. value	0.421	0.121	0.013
	rel. dev.	13%	28%	41%
ABS	abs. value	0.429	0.124	0.014
	rel. dev.	11%	26%	36%
SHGC (I_{sol} = 783W/m² , γ_S = 45°, θ_S = 0°, AI = 45°)				
BSDF		0.161	0.043	0.015
G	abs. value	0.085	0.021	0.008
	rel. dev.	47%	51%	47%
ABS	abs. value	0.088	0.023	0.009
	rel. dev.	45%	48%	41%

Table 10 – Stationary results of SHGC for the Alar Lamella

SHGC (I_{sol} = 783W/m², γ_S = 90°, θ_S = 0°, AI = 0°)				
Slat angle		**0°**	**45°**	**60°**
BSDF		0.477	0.431	0.179
G	abs. value	0.336	0.301	0.129
	rel. dev.	29%	30%	28%
ABS	abs. value	0.340	0.318	0.135
	rel. dev.	29%	26%	24%
SHGC (I_{sol} = 783W/m², γ_S = 45°, θ_S = 0°, AI = 45°)				
BSDF		0.441	0.062	0.051
G	abs. value	0.330	0.051	0.046
	rel. dev.	25%	17%	9%
ABS	abs. value	0.353	0.051	0.047
	rel. dev.	20%	17%	8%

4.2 Quasi-static results

The quasi-static results show a very good agreement for the external raffstore. In the case of the specular Alar Lamella, the difference between the BSDF model and the simplified approaches increases with lower slat angles (Table 11). This can be caused by a lack in detail modelling for the simplified models as mentioned in 2.1.

Table 11 – quasi-static results for the cooling load of both systems

Slat angle	0°	45°	75°
Raffstore	[kWh/m²]	[kWh/m²]	[kWh/m²]
BSDF	29.99	10.45	3.00
G	27.57	9.34	3.25
ABS	28.01	9.44	2.67
Alar	[kWh/m²]	[kWh/m²]	[kWh/m²]
BSDF	35.97	20.85	12.07
G	24.47	17.68	8.59
ABS	26.66	17.94	8.73

The following graphs show the hourly trend for the resulting room temperature (TAIR) in Fig. 8 and inner glazing temperature (TIGL) in Fig. 9.

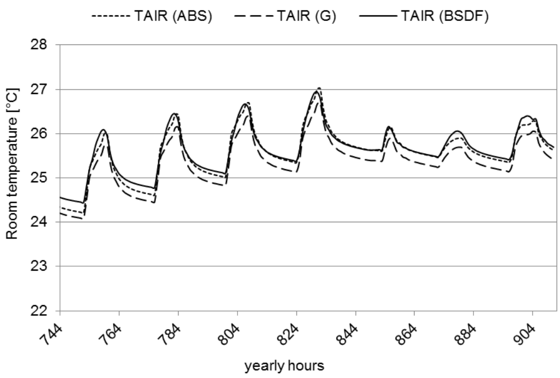

Fig. 8 – Room temperature (Raffstore) - winter condition

The room temperature shows a very good agreement of the Abs-model with the BSDF model in the winter period. In the summer period there is an almost perfect correlation between all approaches for this certain period.

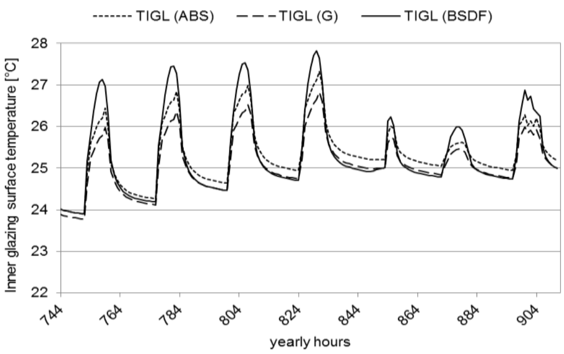

Fig. 9 – Inner glazing temperature (Raffstore) - winter condition

As in case of the simplified methods, the wall gain (secondary heat flux) is calculated externally and not directly within the window model like in the BSDF-model, the results show a high sensibility on linking the wall gain whether inside or outside the glazing. In the case of the external raffstore, the highest result correlations with the BSDF model are reached by linking the wall gain on the outer pane. In the case of the Alar Lamella, which is positioned in-between the glazing, the wall gain is partly linked on the inner and outer pane surface to get best result correlation.

4.3 Dynamic results

In Table 12 the dynamic results for the yearly heating and cooling load for the reference room with both systems and all three models are listed.

For all situations the simplified models show a good correlation – in direct comparison to the BSDF-model the results are slightly higher for both systems.

Table 12: Results for dynamic simulation

Raffstore	Q_{HEAT} [kWh/m²a]	Q_{COOL} [kWh/m²a]
BSDF	12.07	4.45
G	16.41	7.02
ABS	17.32	6.11
Alar Lamella		
BSDF	8.87	6.51
G	11.18	10.90
ABS	10.11	13.09

5. Conclusion

In this paper comparative simulations between the complex BSDF-model and two simplified approaches based on a bi-directional SHGC are presented.
The simplified approaches and the BSDF method are based on the same modelling concept by separating beam and diffuse radiation as well for the individual optical and thermal modelling. Nevertheless, a clearly reduced effort in detailed modelling, especially of the blind layer compared to the complex model in the ISO15099, can be seen. Shortcomings in detailed physical modeling are compensated by empirical validation and individual correction factors depending on the modelled system. Further investigations into these aspects by validations with measured data will be done.

As a conclusion, the simplified methods show, compared to the comprehensive BSDF data, an efficient and flexible modeling of CFS with less complex input data necessary. At the same time, the simplifications and assumptions undertaken fit specific systems settings. This fact leads to necessary pre-studies in order to fit the model to the individual system, which is rather more work compared to the flexible BSDF concept.

6. Nomenclature

SHGC	Solar heat gain coefficient (-)
Q_{Cool}	Cooling load (kWh)
I_{Window}	Radiation on Window (m)
Area	Window area (m²)
I_{sol}	Solar radiation (W/m²K)
γ_S	Solar zenith angle (deg.)
θ_S	Solar azimuth angle (deg.)
AI	Angle of Incidence

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