ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

An hourly-based performance comparison of an integrated micro-structural perforated shading screen with standard shading systems

David Appelfeld
Technical University of Denmark

Andrew McNeil
Lawrence Berkeley National Laboratory

Svend Svendsen
Technical University of Denmark

Environmental Energy Technologies Division
Building Technology and Urban Systems Department

2012

To be published in *Energy and Buildings* (2012)
DOI:10.1016/j.enbuild.2012.03.038.

DISCLAIMER

Energy and Buildings (2012)
doi:10.1016/j.enbuild.2012.03.038.

An hourly-based performance comparison of an integrated micro-structural perforated shading screen with standard shading systems

David Appelfeld[1,a], Andrew McNeil[b], Svend Svendsen[a]

[a] *Department of Civil Engineering, Technical University of Denmark, Brovej, Building 118 DK-2800 Kgs. Lyngby, Denmark*
[b] *Building Technology and Urban System Department, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720*

Abstract
This article evaluates the performance of an integrated micro structural perforated shading screen (MSPSS). Such a system maintains a visual connection with the outdoors while imitating the shading functionality of a venetian blind. Building energy consumption is strongly influenced by the solar gains and heat transfer through the transparent parts of the fenestration systems. MSPSS is angular-dependent shading device that provides an effective strategy in the control of daylight, solar gains and overheating through windows. The study focuses on using direct experimental methods to determine bi-directional transmittance properties of shading systems that are not included as standard shading options in readily available building performance simulation tools. The impact on the indoor environment, particularly temperature and daylight were investigated and compared to three other static complex fenestration systems. The bi-directional description of the systems was used throughout the article. The simulations were validated against outdoor measurements of solar and light transmittance.

Keywords: shading, complex fenestration system, solar gains, daylight, building performance modeling

1. Introduction

Buildings are responsible for usage of significant amount of the energy and account for 40% energy consumption in Europe and the USA. Energy reduction by buildings has become an important part of energy policy and is reflected in building regulations, which require decreased total building energy demand [1, 2]. The largest energy usage is attributed to heating, cooling and electrical lighting.

Optimization of window elements can reduce energy consumed for heating, cooling and electric lighting. Optimization strategies consider heating by increasing solar gains, cooling by providing solar protection and lighting by utilizing daylight [3]. All the functions cannot be addressed by a standard window and the traditional windows have to be combined with shading systems, which then can be described as complex fenestration system (CFS). The challenge is to evaluate those

[1] Corresponding author. Tel: +45 45251856; fax: +45 45883282, email address: dava@byg.dtu.dk

parameters in an interconnected context for CFS performance, since some of the functions are contradicting for static systems, e.g. increasing solar gains in winter while providing shading in the summer [4].

In recent decades, new and renovated buildings have become increasingly insulated and air tight. These steps lower building heating loads but they also increase risk of overheating by capturing excess solar gains, especially in office buildings. Removing overheating by mechanically cooling is expensive and can negate the savings from solar gains in the winter, and thus cooling loads are growing in importance. Contemporary commercial and institutional buildings typically have a low heating and high cooling loads as they have high internally-generated loads by people/lights/equipment and have well-insulated envelopes. Residential buildings have relatively low internal loads vs. their envelope loads. [4]. Solar shading is an effective strategy to reduce overheating and diffuse direct sunlight thus reducing energy consumption [3]. There are many options available for shading systems and it is difficult to precisely describe the energy performance impact of a non-standardized solution [5, 6]. Many of the CFSs have angularly dependent solar and light energy properties but use normal-incidence glazing values of the performance indicators, e.g. total solar energy transmittance. The normal-incidence value description is not an accurate indicator for angularly dependant systems, which need to be described with bi-directional data [7]. The limitations of the available simulation tools and testing methods can be overcome by performing state-of-the-art simulation and its validation with measurements [8].

The main motivation for this research is to establish a procedure for generating information, which can be used during product development of CFSs or an initial phase of building design. This paper focuses on the performance modelling of CFSs and comparison between types. The results of the simulations were compared against measurements taken outdoors and in a laboratory. The aim is to determine the performance criteria of the tested CFSs to indicate impact on the energy and indoor climate in the occupied spaces.

2. Method

Performance is simulated for several shading systems and a comparison is based on the evaluation of various aspects. The bi-directional transmittance simulation results compared to measurements. The performance evaluation is performed with several steps, starting with the shading layer and ending with shading system impact onto a reference room. The design criteria for widows and CFS in modern buildings are:

- Energy use - heating, cooling, electrical lighting
- Thermal comfort - overheating
- Visual comfort - daylight, glare, view to outside

These criteria are interdependent, in this study they are addressed in the context of the following aspects: facade orientation, building location, time of day and year, window size, window position on facade, shading strategy, and human factors (view, comfort and temperature).

The building location determines the climate, including the sun position and sky luminance distribution, which is further dependent on the actual time/date. The central criteria for this article is angular dependant light transmittance (Tvis) and solar transmittance (Tsol) of the CFS. With these parameters the solar heat gain coefficient (SHGC) could be described, which is also referred as the total solar transmittance (g-value) and is central in determining cooling loads of buildings. The thermal transmittance of windows (Uw-value) is one of the major energy performance characteristics controlling heat loss. Transmittance refers to both Tvis and Tsol further in the paper if not specified otherwise.

In this paper, the interconnections of the above parameters are illustrated in case examples presented throughout the paper. Annual performance simulations are carried out when possible.

2.1 Complex fenestration systems

This study focused on a micro structural perforated shading screen (MSPSS) which is made of an insulated double glazed unit with low-e coating on surface 3 and the MSPSS on surface 2. The MSPSS is made from a stainless steel sheet with elliptical holes smaller than 1mm. The holes are cut in a downward direction (when viewed from the inside) to reduce transmission from sources above the horizon and increase transmission from below the horizon. MSPSS was selected because the angular dependence is not symmetrical about the normal making it difficult or impossible to evaluate with standard simulation tools. The MSPSS combines solar and glare protection, provides direct view out and is not included in any standard testing software. Fig. 1 shows a side-by-side view through the MSPSS with an unobstructed view. From observations the view appears less obstructed when viewed at a greater distance. The picture is slightly blurry as it was necessary to focus on the shading layer and the background was in the distance.

Figure 1. View through MSPSS (left), unobstructed view (right)

In order to have a complete understanding of performance, the tested CFS is compared to references systems. MSPSS was compared to clear double glazed windows, without shading, with horizontal venetian blinds, and with a semi-transparent roller shade. The clear glazing reference case was studied to demonstrate the effect of the shading and glazing separately.

Venetian blinds were used as a comparison because they are a conventional system that also provides shade and permits view. A roller shade was also used as a reference because it blocks solar gains and glare more efficiently then the semi-opened system, however, unlike MSPS and Venetian blind, it blocks the view to outside.

All the shading systems were simulated with the same glazing. In all cases, the shading was located between the glass panes to limit the variations in the energy performance of the individual systems.

2.2 Determining bi-directional transmission characteristics

Tsol and Tvis are the fundamental performance indicators for CFS and all the following calculations were based on them. The calculations are carried out in several sequential steps with increasing level of information.

2.2.1 BSDF generation via simulation

Radiance was used to generate a bi-directional scattering distribution function (BSDF). Radiance is an accurate backward ray-tracing Unix-based program that has been validated for such purposes [9]. The new software development allows generating a BSDF, which describes transmittance dependent on incident angle (IA). A model of the MSPSS was created using detailed geometric drawings from the manufacturer and reflectance measurements of an un-perforated sample also provided by the manufacturer. Radiance's program genBSDF was used to generate a BSDF matrix [10]. The genBSDF program generates blocks of values which describe 145 Klem's incidence angles for one of 145 oppositely placed outgoing directions [11]. This data was validated against goniophotometer measurements for a few incident angles [12]. The validated BSDF was used to calculate Tsol and Tvis of the glazing unit with the shading screen.

2.2.2 Comparing measurement with simulations

Measurements were taken of the MSPSS taken to ensure that daylight simulations using BSDFs would reliably reproduce real-world results. Measurements were taken outdoors in order to include direct light from the sun and diffuse light from the sky reproducing the type of environments experienced by a real building. Both components of daylight are important because together they determine indoor daylight conditions, unlike cooling loads which are highly dependent on the direct sunlight [3]. Measurements were taken on clear days in June and July because clear skies are the most reliably reproduced of the CIE sky types (and clear skies are commonly occur in the summer in Denmark, where the measurements were taken)[9]. The sample was rotated to imitate different incident azimuth and altitude angles so that many IAs could be tested in a short time. The dynamic sample positioning introduced inconsistent ratios of exposure to sky and ground for the sample. To counteract this, the sample was positioned in the simulation to match the position of the sample during each measurement, and thus the measurements and simulations were analogous.

To quickly rotate samples, a movable rig was used, that safely held the test sample and allowed to adjust the sample with respect to the sun. Due to the size of the sample, only IAs up to 60° could be measured, as accuracy could not be ensured with higher IAs. Transmittances for higher

IAs were derived from simulations. The test rig, shown in Fig. 2, consisted of a mounted sample and two sets of illuminance and irradiance meters, which were aligned to the surface of the sample. One illuminance and irradiance sensor was placed behind the sample, close to the glass surface, to measure the light transmitted by the sample. The other illuminance and irradiance sensors were placed on the side of the measurement rig to measure light incident on the sample. Relative transmittance of the sample was calculated by dividing the transmitted measurement by the incident measurement. Using relative measurements accommodates surrounding with obstacles without introducing large error to the results.

A solar pointer, shown in Fig. 3, was used to accurately align the sample for each IA. The pointer, of known length, was positioned perpendicular to the surface of the glazing and a measuring. The measuring grid is marked with shadow points for each incident angle. The sample can be moved until the shadow from the pointer aligns with the shadow point for the desired incident angle. The process allows for accurate sample alignment, reducing errors in IA. Every IA was measured with and without the sensors shaded from the direct light to determine diffuse and direct radiation. Each measurement was repeated at least twice to reduce measurement error.

By recording the time, sun position, total horizontal hemispherical diffuse illuminance and direct normal illuminance, it was possible to reproduce sky conditions in the simulations. Clear glazing with known properties was tested in the same manner to validate the both the measurement and simulation procedures. The sensors were calibrated before the measurements to minimize the sensor precision error.

The first preliminary test was carried out without a sample to determine how much the test rig shades the sensors. The test verified that this error was smaller than the accuracy of the sensors and therefore could be neglected. The rig was equipped with a shading box behind the sample to shade specular reflections from the sample's back surface and the ambient environment.

Figure 2. Movable measurement test rig with sample mounted

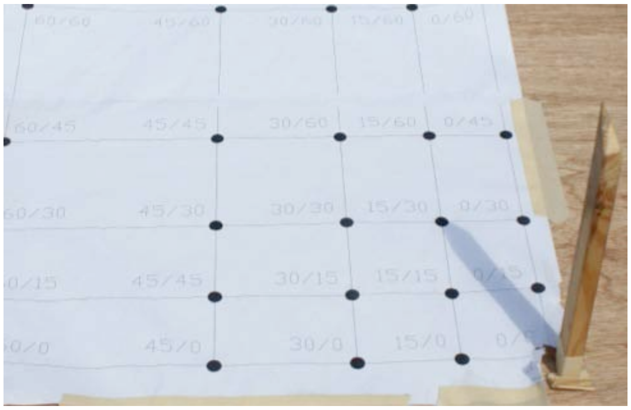

Figure 3. Solar pointer and measurement grid, The current IA is azimuth of 15° and altitude 30°

2.3 System performance simulations

2.3.1 Model description

The simulated model was a single office for three occupants with dimension of 3.5m wide, 5.4m deep, and 2.7m high. The room model is based on the test office in IEA task 27 in order to have standardized model [13]. The window varies from the test office and is modelled as one large window of 1.2m x 2.5m with a 1m sill. The surface properties of the room are listed in the Table 1. The plan view of the room with the furniture is shown in Fig. 4, including view directions. The view height is 1.2m above the floor, which corresponds to eye-level for a sitting person.

Table 1. Model's surface properties

	Wall	Ceiling	Floor
Reflectance	0.5	0.8	0.3

The thermal model of the office was built with an assumption that all adjacent offices have the same temperature, except the exterior wall and window, which were exposed to the outdoors. Thermal transmittance of the external wall was 0.5W/m^{2}K and the infiltration was set to 0.5AC/h.

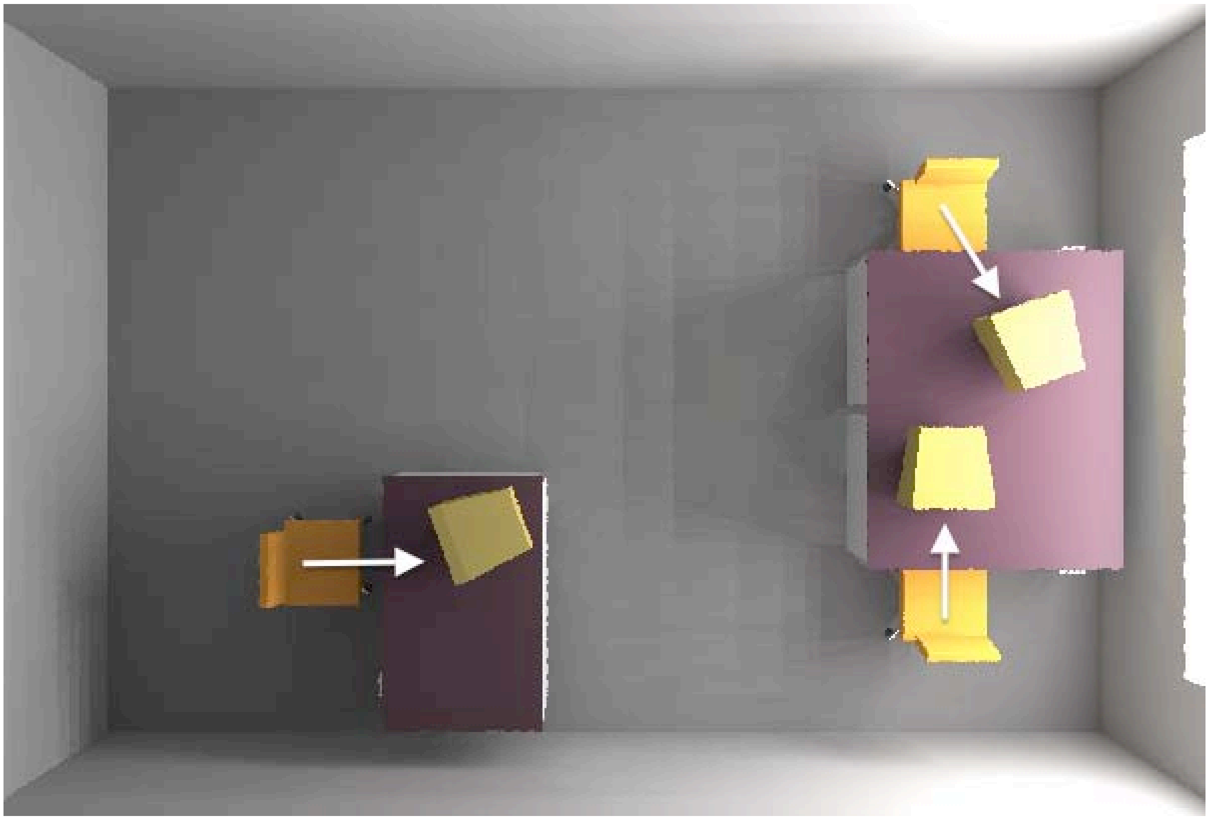

Figure 4. The plane view of the office with view directions

2.3.2 Annual Daylight Simulations

Radiance was also used to simulate of the daylight conditions in the reference office. Work plane illuminance was simulated throughout a year and daylight autonomy was used to evaluate the annual results. The heating and cooling loads of the tested office were calculated in ESP-r, which allows use bi-directional information about solar energy transmittance of CFS.

The Radiance three phase method (TPM) allows users to calculate the annual daylight performance of CFS using bi-directional information without a significant increase of the computational time. The TPM is based on the multiplication of four matrices describing light through an interior (view matrix), fenestration (transmittance matrix), exterior (daylighting matrix), and sky distribution (sky vector). This process allows for a relatively quick dynamic light and solar radiation simulation over a year. Additionally, by changing only one of the matrixes various aspects could be effectively investigated: different orientations by changing the daylighting matrix, location by changing sky vector, and different CFS by using different BSDF [5].

2.3.3 Electrical light savings and daylight

The electrical light energy was computed for all four scenarios, when no daylight is utilized to fulfil required illuminance criteria. Two work plane illuminance criteria for offices were used: 500lux according to standard CEN-EN 15251 [14] and 300lux according to IESNA [15, 16]. The office was divided into three 1.8m deep and 3.5m wide lighting zones, with zone 1 closest to the window and zone 3 furthest from the window. Each zone was separately controlled. The relatively small zones were used mainly for investigational purposes to show the potential lighting energy savings.

Two control strategies were considered: on/off switching and bi-level switching. For on/off control the electric lighting in a zone was switched off when daylight alone provided the required work plane illuminance. With bi-level switching the electric lighting could be switched to half output (by switching off half of the lamps in the zone) when the daylight illuminance met half of the work plane illuminance criteria and could be switched off entirely when daylight illuminance met the full work plane illuminance criteria.

The lighting power density (LPD) for the working plane illuminance (WPI) of 500lux of 15W/m^2 was derived from standard EN 15193 [17]. Electric lighting savings were based on the linear substitution of electrical lighting by daylight and thus are idealized. For the WPI of 300lux an equivalent LPD of 9W/m^2 was used.

Daylight was evaluated using daylight autonomy (DA), which is the percentage of hours satisfying the minimal design WPI in the total number of working hours in a year [18].

2.3.4 Glare

Glare was evaluated because visual comfort of the CFS is an important aspect of the CFS performance. Daylight Glare Probability (DGP) was selected as a glare index because it is based on an extensive human evaluation study [19, 20]. Glare analysis was performed for all three working positions in the office. Glare was assessed on an annual basis focusing on the working hours between 8:00 and 18:00.

2.3.5 Net Energy Gains

The glazing unit properties were used to calculate net energy gains (NEG). The NEG calculation method is based on a window's solar gain minus its heat loss based on outdoor temperature during the standard heating season [21, 22]. NEG is a simplified method that describes the relationship between a window and a building, in kWh/m^2. The formula for NEG is:

$$Eref = g.I - U.D \qquad (1)$$

Where I is the coefficient for solar gains and D is coefficient for heat loss. For Denmark the total coefficient for solar gain is 280.6kWh/m^2, for North 105kWh/m^2, for South 431kWh/m^2 and for East/West 232kWh/m^2. The solar gain coefficients are further multiplied by an assumed shading factor 0.7 [23]. The assigned contribution from South is 41%, North 26% and East/West 33%. The heat loss coefficient D for the heating season in Denmark is 90.36 kKh [21].

2.3.6 Energy performance

Kuhn et al. found that heating demand in the cold climates calculated using standard evaluation techniques was overestimated up to 23% and that cooling demand was underestimated up to 99%

[24, 25]. This study aims to determine if bi-directional information, especially angle dependant g-value, provides more accurate results for heating and cooling loads [26]. The evaluated location, Copenhagen, Denmark, is located in a Nordic climate, which could be considered as a moderate climate zone, however the cooling loads have to also be taken into account, as they are a significant part of the energy consumption in modern buildings [27]. Furthermore energy performance was calculated for Prague, Czech Republic, and Rome, Italy, to illustrate the performance based on the location.

The ESP-r model for using bi-directional information about solar energy transmittance is called Black-Box-Model and was validated [6, 24, 26]. The model 5° resolution for azimuth and altitude incident angles on the surface of the CFS.

3. Results

3.1 Outdoor measurements vs. Radiance simulation

The comparison of Radiance simulation results against outdoor measurements of Tvis and Tsol is shown in Fig. 5. The difference in the corresponding curves is between 0% and 4%, except for visible transmittance at the IA of 60° where the relative error is around 18%. This error was caused by comparing the relatively small values and in absolute numbers would not be significant and/or by slightly off-position of the measuring rig. The radiance simulation results were generated using the TPM.

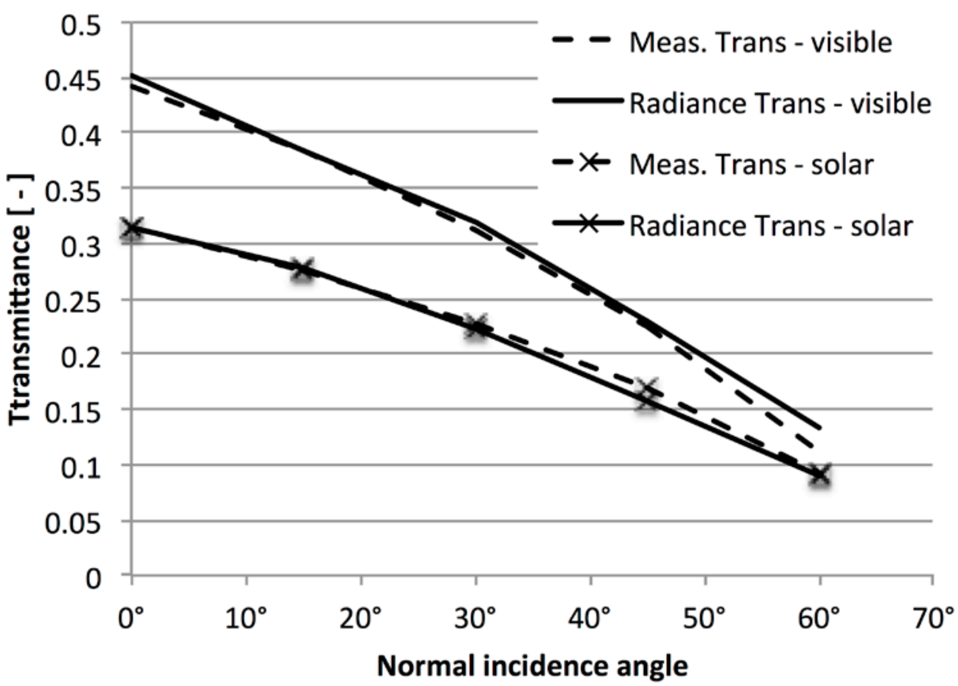

Figure 5. Comparison of measured and simulated Tvis and Tsol

3.2 BSDF

BSDF's are generated by programs genBSDF and Window6 to provide a more comprehensive description of the shading properties dependency on the azimuth and altitude of the sun. These BSDFs were validated by McNeil et al. in a connected study [10]. Fig. 6 contains visualizations of results for the front Tvis of the four shading systems, independent of window orientation and location. For a better understanding of the relation between the transmittance and IA the annual sun path for Copenhagen is added to the charts.

As expected the solar transmittance is the highest for the clear glazing and is symmetrical around the centre. The woven roller shade has the lowest transmittance, as it evenly reduces the transmittance and blocks view to the outside. The MSPSS and venetian blinds are more IA dependent and allow higher transmittance for the negative altitude. In other words, the light is blocked more effectively from sky. Both shadings have their highest transmittance around −15° of altitude.

For the locations of Prague and Rome the shading efficiency will be higher because the sun altitude is also higher. The solar gains can be utilized by angularly dependent systems during the winter months when the sun is low and transmittance is higher. Additionally, effective shading occurs during the summer when the sun altitude is higher. The maximum light transmittance of the MSPSS and venetian blinds was between 0.5 and 0.6, while for clear glazing it was up to 0.8. The glazing with roller shade had high shading effects and the transmittance was as low as 0.2.

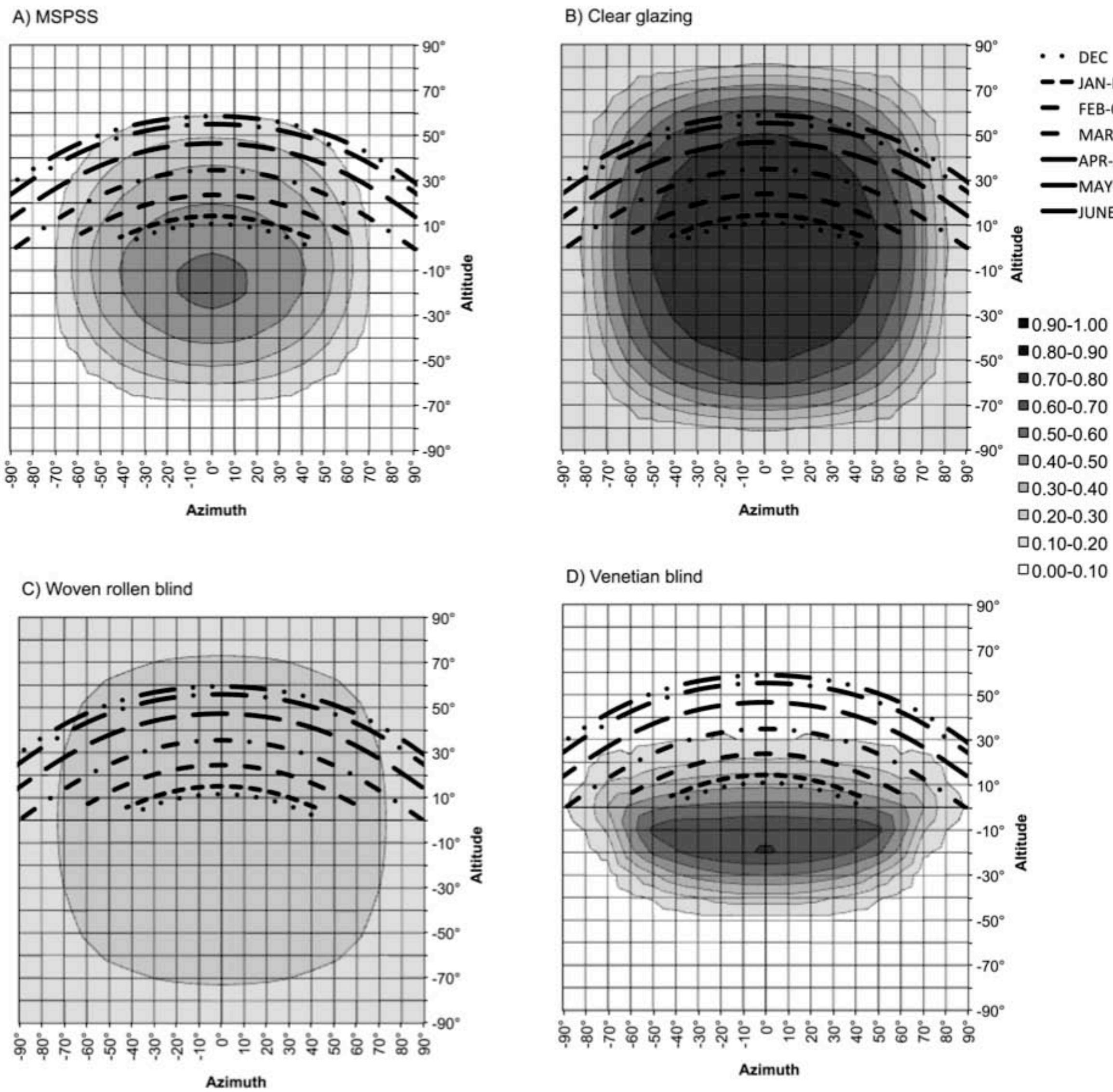

Figure 6. Visible transmittance of CFSs with solar path of Copenhagen

3.3 Daylight autonomy

Fig. 7 contains daylight autonomy (DA) results for all four systems on South facing facades. The shaded bands illustrate the percentage when a certain level is reached. For example, for a glazing with MSPSS, 80% of working hours have an exposure of at least to 216lux at a distance of 0.5m from facade.

A logarithmic scale was used to provide better visibility of smaller values because the clear glazing provided high illuminance closer to the window and far exceeded other values in the chart, which were still valuable and fulfil the requirements. As expected, DA was higher close to the window and DA was lower in the back of the room. At the back of the room DA did not satisfy the lighting requirements. The highest illuminance was provided with the clear glazing with WPI 10klux close to the facade, which far exceeds WPI criteria thus the energy cannot be fully utilised and may indirectly cause a glare and overheating. The solutions with lower relative

WPI can still serve purpose without the risk of a glare and overheating. While there is not a direct correlation between a WPI and glare, values above 4500lux are generally not desirable [16, 19, 28]. The illuminance levels for systems with shading systems were similar with slightly better performance for MSPSS.

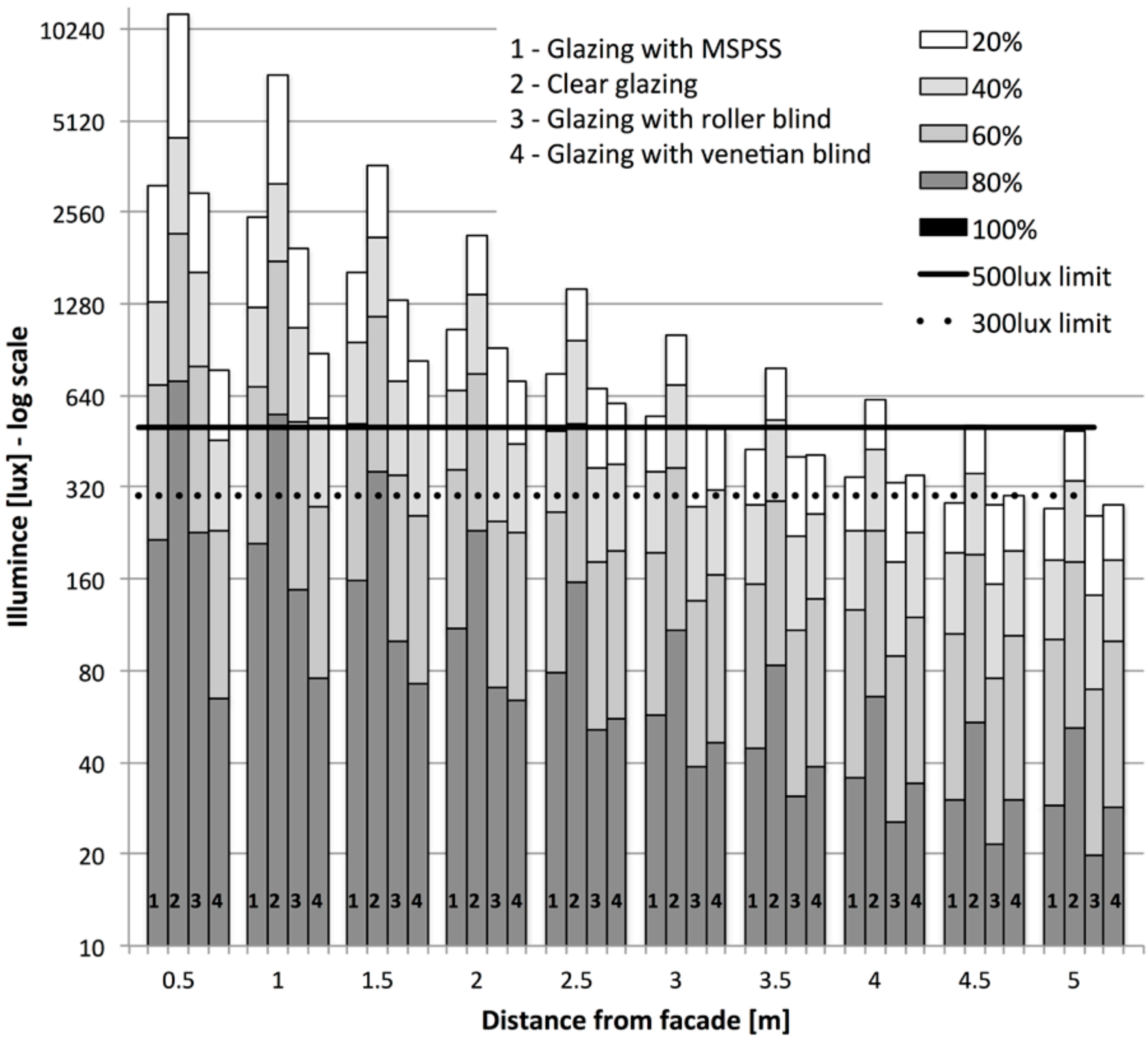

Figure 7. Daylight autonomy

3.4 Electrical light savings

The analysis assumed that the light in a zone was switched off when the daylight illuminance fulfilled the WPI criteria (on/off control). In addition, bi-level switching was considered, which allows the LPD to reduce by 50% when half the WPI criteria were met by daylight illuminance (i.e. switching off half the lamps in a zone). In the Figs. 8 and 9 the savings were split by on/off and bi-level lighting control. The on/off savings mean fulfilment of the criteria 300lux or 500lux, and bi-level were the additional savings by introducing bi-level control strategy.

The largest savings generally occurred in zone one, which was commonly saturated by daylight.

Zone 3 is less exposed to daylight and thus the savings were smaller.

By illustrating the difference when the light was either fully or 50% switched off it was possible to see that in the front of the room daylight reached higher illuminance and the light was completely off, while in the back off the room the major power savings were because the bi-level lighting control system. Therefore the savings were influenced by the light control strategy. Furthermore, the savings followed illuminance levels in Fig. 7. This indicated that it was possible to shade excessive illuminance, while providing the savings of the lighting energy, as the clear glazing did not produced significantly higher savings. Additionally there was not significant difference between scenario with 500lux and 300lux.

The savings in zone 3 were mainly during the winter period when the sun is low and the penetrated light could reach the back of the room.

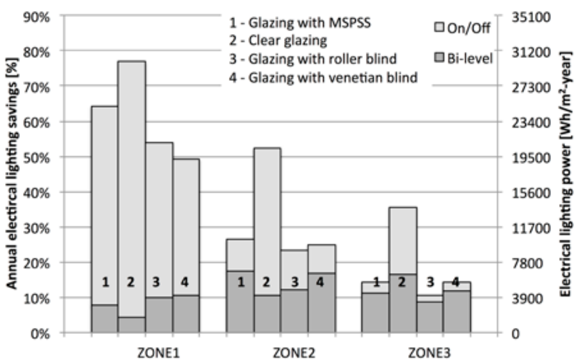

Figure 8. Electrical light saving for work plane illuminance of 500lux

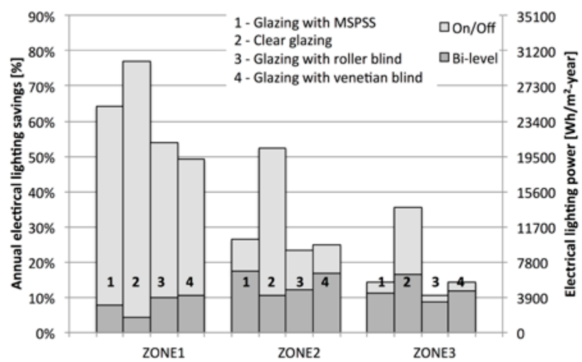

Figure 9. Electrical light saving for work plane illuminance of 300lux

3.5 Glare assessment

Fig. 10 shows Daylight Glare Probability (DGP) for the four systems and three views. The graphs display the glare rating for every hour during the whole year. All three evaluated views are marked and illustrated in Fig. 4. View 1 was parallel along the window pointing to East and thus the higher DGP values occurred before noon. View 2 faced to Southeast and higher DGP values were during afternoon. View 3 was oriented to the window, South, and higher DGP index was at noon.

The most glare occurs with clear glazing, as no direct sunlight was blocked. Conversely, the least glare occurs with the roller shade, particularly for view 1 and view 3 which experience no glare. An expected result would be that the roller shade would also prevent glare for view 2, however the position was close to the source and the roller shade was partially transparent, therefore glare occurred.

Of the three views studied, view 2 experiences the most glare. Glare occurs year round with clear glazing, while glare occurs only seasonally with the shading systems.

The venetian blinds block slightly more glare than MSPSS in all views, which was caused by more selective transmittance of the venetian blinds, with the lower transmittance under higher IAs. This was also possible to assume from the carpet plots in Fig. 6 and later in Fig. 12, describing angularly dependent transmittance. The observation would not be possible by considering transmission at normal-incidence only.

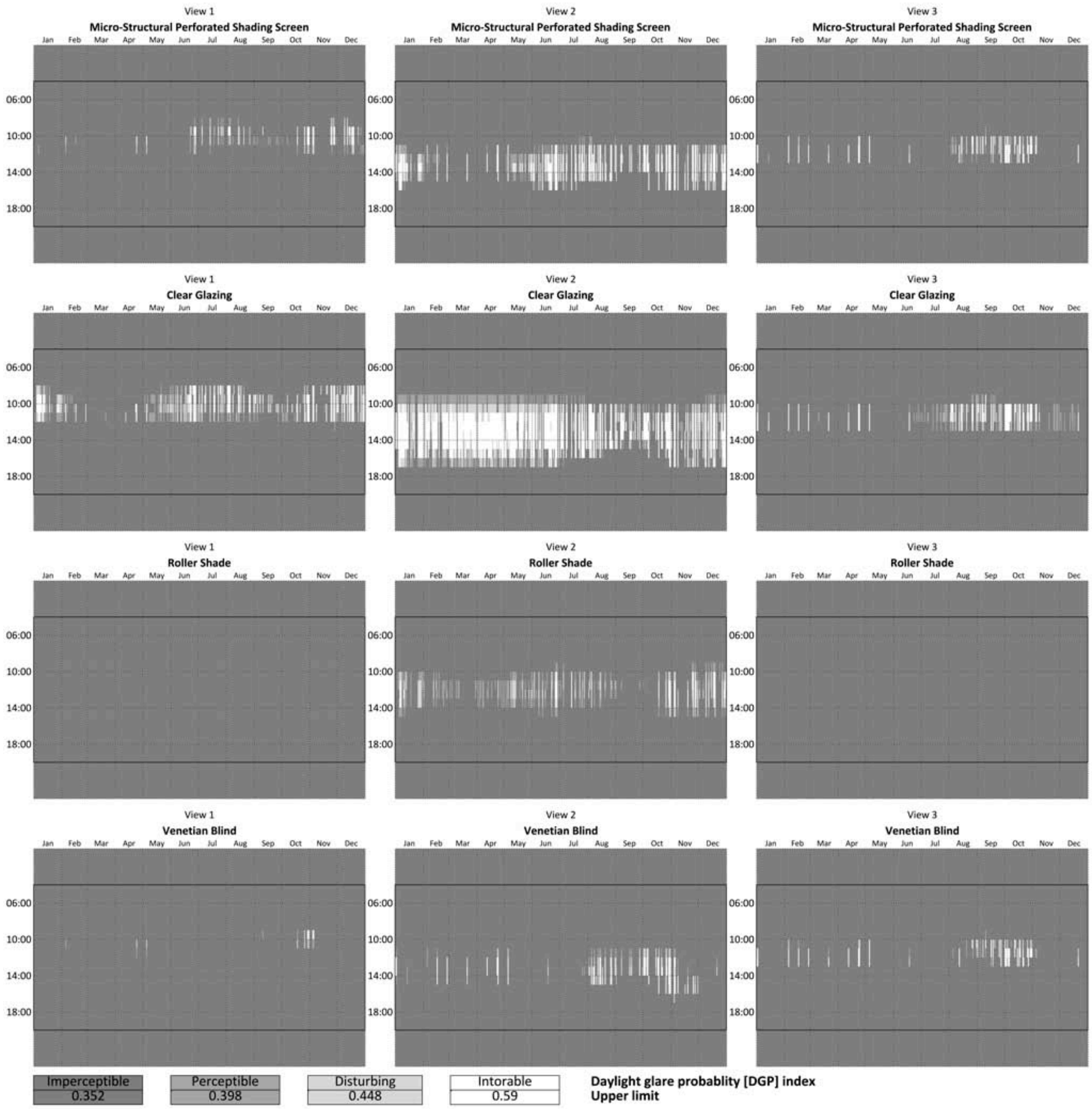

Figure 10. Annual plots of the DGP for three views and all CFS in the location of Copenhagen

3.6 Net energy gain

The total solar energy transmittance (g-value) is the fraction of the actual solar energy that passes through the window. The CFSs were modelled in Window6 with shading located between the glass panes to avoid favouring internal or external shadings. Table 2 contains the centre pane U-values and normal incidence g-values. The results in Table 2 for individual sides do not include assigned percentage of the distribution to the individual orientation. The result of NEG for all four shading solution in the respect of the facade orientation is in Fig. 11.

Table 2. Energy performance indicators of selected CFS and NEG

	Centle Ug [W/m²K]	Normal-incidence g-value [-]	NEG [W/m²K] All	North	South	East/West
MSPSS	1.23	0.37	**-38.8**	-84.1	0.1	-51.3
Clear glazing	1.25	0.62	**7.8**	-67.9	72.6	-13.2
Woven rollen shade	1.16	0.35	**-37.4**	-79.8	-1.1	-49.2
Venetian blind	1.10	0.49	**-3.5**	-63.5	47.8	-20.1

MSPSS had the lowest NEG, which is mainly caused by a negative contribution from a north facade and low solar gains contribution from South. Nevertheless, shading should be used primary for the south facade and considered for the east and west facade. The MSPSS results show that the MSPSS reduces overeating, thus the MSPSS is considered to perform well with regards to shading. The north facade is not typically equipped with shading, so the negative performance of shading solutions on the north can be overlooked. The main focus was on the south orientation values since the simulation model was South facing. Fig. 11 illustrates NEG in a relation to the variable g-value. In the case of the large south window the rest of the CFSs generated large solar gains and would cause the space overheating. NEG does not penalize the overheating causing the cooling loads. Therefore the energy performance of the room dependent on the angular properties of the shading including cooling loads which is discussed in the next section.

The clear glazing and the glazing with roller shade had relatively constant NEG up to the normal surface IA of 40°, while the MSPSS' and venetian blinds' NEG decreased sharply from IA of 0°. The sharp drop in g-value is a result of the inclined structure of both shades. The solar altitude in northern Europe (Denmark) is mostly below 40° with the maximum below 60°. For shading purposes, a progressive g-value is efficient because it provides the most shading in summer when direct solar radiation is most intense and least desirable. The g-value of all tested solutions, shown in Fig. 12, is similar to the front visible transmittance in Fig. 6. The total solar transmittance is less concentrated and the energy is transmitted through wider range of IAs compared to the visible transmittance.

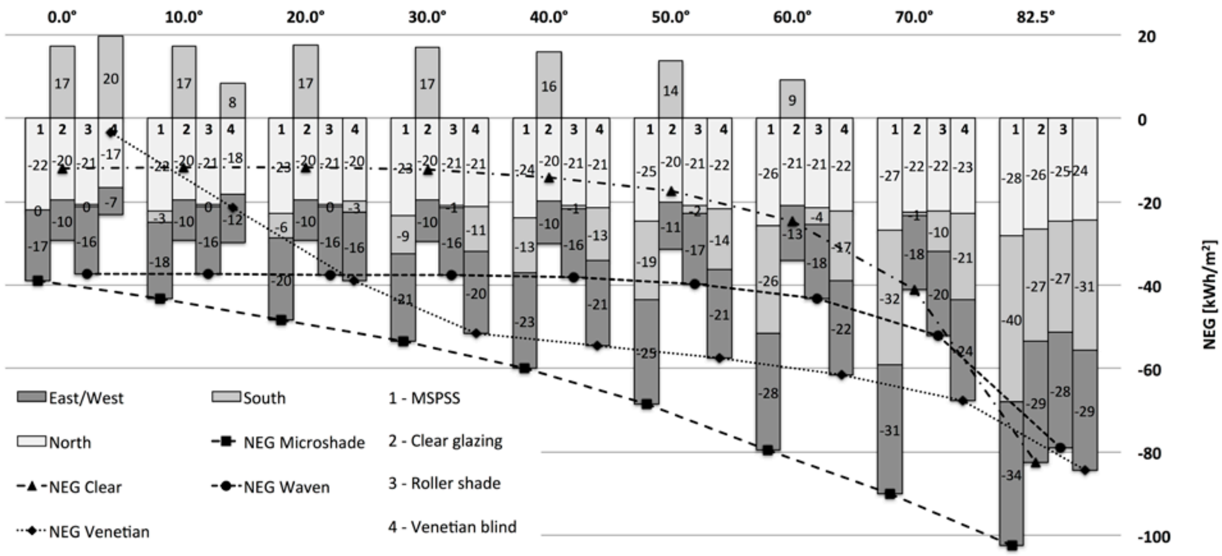

Figure 11. NEG for four different CFSs, split for different orientation and dependent on IA

3.7 Energy loads

Heating and cooling loads were evaluated based on the ESP-r simulation model. The model allowed testing different shading systems with the detailed bi-directional transmittance properties. The large sources of energy for heating and cooling were assigned to the model in the way that they were never exhausted. Table 3 contains the results for the heating and cooling loads. Heating loads excluded solar gains and considered only the energy needed to maintain the set point for heating of 20°C, during working hours, and 15°C outside the working hours. Heating loads were relatively low since the building was well insulated. The cooling loads were calculated using the energy needed to cool the space when the air temperature was above 26°C. The largest cooling loads occurred with clear glazing, which did not provide any shading. All shading solutions provided similar shading protection and reduced cooling loads by 20% to 30% compared to the window without the shading. The larger heating loads for Prague compare to Copenhagen were caused by a fact that in Prague the temperatures in the winter months are lower as well as there are more extreme temperatures.

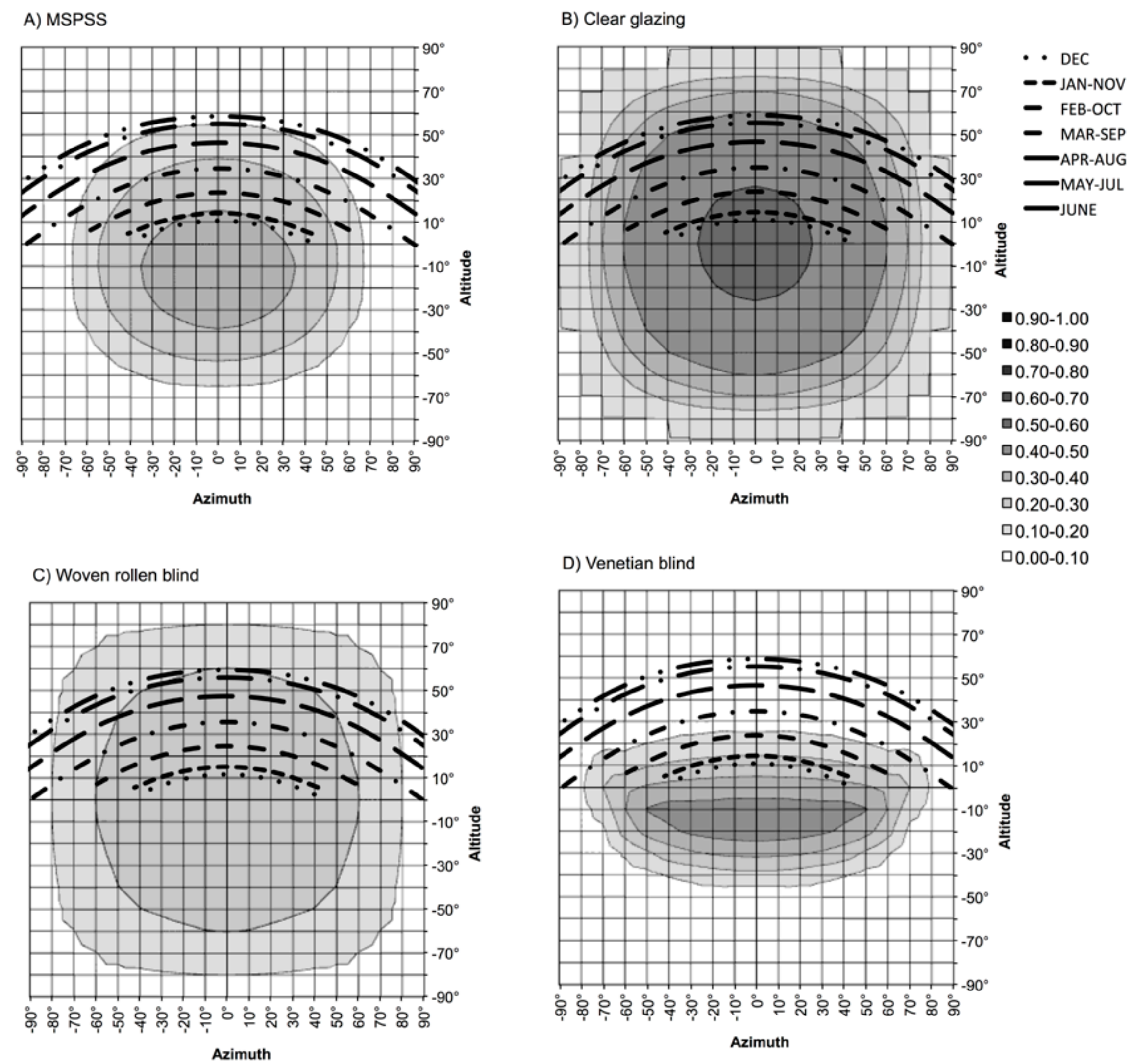

Figure 12. BSDFs for total solar energy transmittance of the CFSs with sun path of Copenhagen

Table 3. Energy loads for heating and cooling for all CFSs and investigated locations

Location	Energy performance [kWh/m²/year]							
	MSPSS		Clear		RollerShade		VenetianBlind	
	HL	CL	HL	CL	HL	CL	HL	CL
Copenhagen	8.5	22.5	6.6	30.4	9.0	22.8	9.3	20.3
Prague	12.3	24.4	10.5	30.4	12.7	24.3	13.2	23.2
Rome	0.0	63.5	0.0	78.1	0.0	63.9	0.1	59.4

Note: HL - heating loads; CL - cooling loads; MSPSS - micro structiral shading screen

4. Discussion

The results describe overall performance of all four CFSs and the complexity is addressed by interconnected evaluation parameters. It was important to validate the simulation results for bi-directional transmittance against measurements since the study is dependent on the bi-directional transmittance data. The measurements and simulations correlate reasonably and thus the results are trustful and the model of the MSPSS is described accordingly to its geometry and properties.

As modern buildings are thermally well-insulated, the importance of shading solar gains for transparent elements becomes more important, especially on the southern and east/west facades, even at higher geographical latitudes. NEG illustrates that even double-glazing provides significant heating gains and has an influence on the overall performance of the building. This conclusion is supported by the results from the energy calculations in ESP-r where the southern climates require more solar protection. When the clear glazing is excluded, all three tested shadings systems provide similar energy performances, however the roller shade reduces visibility and therefore the usage potential is limited because users would likely prefer the other systems. Furthermore, the roller shade system limits daylight penetration and reduces the light energy savings by daylight compared to the more open venetian blind and the MSPSS. On the other hand, shading systems also reduce beneficial heat gains in cold months.

These two aspects are contradictory, as shading would be used during summer and solar heating gains during the winter. The bi-directional description of the performances of the individual systems provides accurate results and is clear description of the properties. By such information, together with knowledge of the local conditions, the building design can be accordingly adjusted to maximise the performance utilization of the particular shading system. From the combination of the results it is possible to see that angularly selective shading systems are the key to energy indicators for cooling and heating. Information about the variable g-value is valuable for northern locations where the higher g-value is useful during winter when the sun is low.

The transmittance of the system is directly linked to the level of daylight. From the combination of bi-directional transmittance and daylight autonomy it could be justified that more daylight be transmitted in during winter months when the daylight levels are generally lower. Higher solar and light energy protection in summer is desirable, as the light intensity is greater. This is the reason for blocking incoming radiation to protect space from overheating and excessive levels of the WPI. The shading systems provide glare protection in addition to shading extensive solar gains. The glare evaluation was performed with the actual sun position at the time of the evaluation, meaning that the light transmittance varied at each time step. In the case of the visual comfort, blocking direct light is necessary, however even the completely closed roller shade caused visual discomfort and glare. The glare is not dependent only on the shading solution, but mainly on the position of a view to the light source, and therefore optimal view direction is critical. As such, it is not fully possible to say that the roller shade performs better or worse than the MSPSS or venetian blinds.

When the focus is on the view out, clear glazing would perform the best, however when the glare is included then it can become the worst. The difference between the MSPSS and venetian blind were minimal regarding the visual performance. However the MSPSS is almost invisible and does not disturb the view as venetian blind does.

The optical and thermal performances of the MSPSS could be improved by placing the layer to the external surface, if a durability of the layer allows exposing the MSPSS to the outdoor environment. An indirect shading efficiency would be increased as an absorbed energy in the glass would be reduced with the shading layer on the external surface. Thermally the glazing with the external MSPSS layer would perform better as the emissivity of the coating is lower than the normal emissivity of glass.

Such system would be suitable for renovations by attaching the shading layer onto the glazing surface of an existing window. However, placing the MSPSS layer on either internal or external surface of the glazing would make cleaning and maintenance complicated as dust would deposit in the microstructure.

Conclusion

A comparison of several performance indicators was carried out for four different CFSs and benchmarked against each other. The bi-directional transmittance simulations were first validated with outdoor measurements prior to using the data in further. There was a strong correlation between the measurements and simulations. To provide an overview of the CFS performance it was necessary to use several interrelated parameters. By using bi-directional information describing CFS it was possible to accurately depict the shading with a high level of understanding in the context of the IA and location. It was found that the angular dependent shading systems provided improvement all year round in providing daylight, heating load reduction by controlling solar gains and decreasing risk of overheating during summer days when the sun altitude is high. The visual comfort depended on blocking direct light by optimal positioning of the shading and the direction of the view. This paper demonstrates that it is possible to evaluate unique shading systems, which are not typically included in the building performance simulation tools. However it has to be noted that the process needs to be automated and included in widely used simulation tools in order to shorten the time of the complete performance evaluation with all consequences.

It can be concluded that the MSPSS performed well compare to the rest of the solutions. The layer provided similar shading effect as the venetian blind. Unobstructed view to outdoor through the MSPSS did not generate extensive glare and the utilization of daylight was kept high.

Acknowledgement

The research was co-funded by the Danish Energy Agency program on research and demonstration of energy savings. The authors would like to acknowledge PhotoSolar A/S for providing the test samples and their co-operation and contribution to this paper.

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231 and by the California Energy Commission through its Public Interest Energy Research (PIER) Program on behalf of the citizens of California.

References

[1] EU, EPBD recast, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast), Official Journal of the European Union (July 2010).

[2] US DOE Office of Energy Efficiency and Renewable Energy, Buildings Energy Databook, US Department of Energy, Office of Energy Efficiency and Renewable Energy, 2005.

[3] J. Carmody, S. Selkowitz, E.S. Lee, D. Arasteh, Window Systems for High-Performance Buildings, W.W. Norton & Company, December 2003, ISBN- 13:978-0393731217.

[4] M.Sala, The intelligent envelope: the current state of the art, Renewable Energy 5 (1994) 1039–1046.

[5] G. Ward, R. Mistrick, E. Lee, A. McNeil, J. Jonsson, Simulating the daylight performance of complex fenestration systems using bidirectional scattering distribution functions within radiance, Leukos (2011), 7(4), 241-261

[6] F. Frontini, T.E. Kuhn, S. Herkel, P. Strachan, G. Kokogiannakis, Implementation and application of a new bi-directional soar modelling method for complex facades within the ESP-r building simulation program, Eleventh International IBPSA Conference Glasgow, Scotland; July 27–30, 2009; p. 936–943

[7] R. Sullivan, L. Beltran, E.S. Lee, M. Rubin, S.E. Selkowitz, Energy and daylight performance of angular selective glazings, in: Proceedings of the ASHRAE/DOE/BTECC Conference, Thermal Performance of the Exterior Envelopes of Buildings VII, Clearwater Beach, FL, December 7–11, 1998, 1998.

[8] A. McNeil, E.S. Lee, Annual Assessment of an Optically-Complex Daylighting System Using Bidirectional Scattering Distribution Functions with Radiance, DOE/LBNL FY10 Technical Report Deliverable.

[9] G. Ward Larson, R. Shakespeare, Rendering with Radiance: The Art and Science of Lighting Visualization, Morgan Kaufmann, San Francisco, 1998.

[10] A. McNeil, C.J. Jonsson, G. Ward, D. Appelfeld, E.S. Lee, Validation of a ray-tracing tool used to generate bi-directional scattering distribution functions for complex fenestration systems, Solar Energy, submitted for publication.

[11] J.H. Klems, A new method for predicting the solar heat gain of complex fenestration systems: I. Overview and derivation of the matrix layer calculation, ASHRAE Transactions 100 (1) (1994) 1065–1072.

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

[13] IEA TASK 27, Performance of Solar Facade Components, 2005.

[14] CEN –EN 15251, Indoor Environment Input for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lightning and Acoustics, European Committee for Standardization, Brussels, Belgium, 2007.

[15] IESNA Lighting Handbook, Illuminating Engineering, 9th edition, July 2000, ISBN-13:978-0879951504.

[16] J. Mardaljevic, L. Heschong, E. Lee, Daylight metrics and energy savings, Lighting Research and Technology 41 (2009) 261–283.

[17] EN 15193, Energy Performance of Buildings—Energy Requirements for Lighting, European Committee for Standardization, Brussels, Belgium, 2007.

[18] C.F. Reinhart, O. Walkenhorst, Dynamic RADIANCE-based daylight simulations for a full-scale test office with outer venetian blinds, Energy and Buildings 33 (7) (2001) 683–697.

[19] J. Wienold, Dynamic daylight glare evaluation, Eleventh International IBPSA Conference Glasgow, Scotland; July 27–30, 2009; p. 944–951

[20] J. Wienold, J. Christoffersen, Evaluation methods and development of a new glare prediction method for daylight environments with the use of CCD cameras, Energy and Buildings 38 (7) (2006) 743–757.

[21] T.R. Nielsen, K. Duer, S. Svendsen, Energy performance of glazings and windows, Solar Energy 69 (Suppl. 1–6) (2000) 137–143.

[22] D. Appelfeld, C.S. Hansen, S. Svendsen, Development of a slim window frame made of glass fibre reinforced polyester, Energy and Buildings 42 (2010) 1918–1925.

[23] EN832, Thermal Performance of Buildings—Calculation of Energy Use for Heating — Residential Buildings, CEN, 1998.

[24] T.E. Kuhn, S. Herkel, F. Frontini, P. Strachan, G. Kokogiannakis, Solar control: a general method for modelling of solar gains through complex facades in building simulation programs, Energy and Buildings 43 (2011) 19–27.

[25] T.E. Kuhn, Solar control: a general evaluation method for facades with venetian blinds or other solar control systems to be used 'stand-alone' or within building simulation programs, Energy and Buildings 38 (6) (2006) 648–660.

[26] T.E. Kuhn, C. Buhler, W.J. Platzer, Evaluation of overheating protection with sun-shading systems, Solar Energy 69 (Suppl. 1–6) (2000) 59–74.

[27] S. Lechtenböhmer, A. Schüring, The potential for large-scale savings from insulating residential buildings in the EU, Energy Efficiency 4 (2010) 257–270.

[28] D. Appelfeld, S. Svendsen, S.T. Borup, Performance of a daylight redirecting glass shading system demonstration in an office building, in: Building Simulation 2011, Sydney, Australia, 2011.