VISUAL PERFORMANCE OF A DAYLIGHT REDIRECTING GLASS SHADING SYSTEM DEMONSTRATION IN AN OFFICE BUILDING

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ABSTRACT

This paper evaluates the daylighting and visual conditions of a building equipped with a prototype external dynamic integrated shading and light redirecting system. The demonstration project was carried out on a building with an open-planoffice. The prototype and original façades were placed on the same floor with the same orientation and similar surroundings. The existing façade was used as the reference for measurements and simulations. The focus of this research project was to employ available simulation tools for performance evaluation. This was accompanied by measurements of the daylight conditions in the investigated space. The prototype system improved daylighting conditions compared to the existing shading system.

INTRODUCTION

The growing demands for energy savings, money savings, and seeking new innovative technologies is the motivation of the research. Available simulation programs cannot evaluate unique complex fenestration systems using standardized methods, since they are mostly created to evaluate specific solutions. The complexity of the assessment can be seen from many perspectives such as energy impact, shape, material, cost and operating cost. Therefore, we have to use more generic and versatile simulation programs and techniques to have the possibility to evaluate the performance impact. Consequently, by the obtained knowledge it is possible to do an evaluation on more standardized level for future solution development.

Additionally, the need to cut down energy consumption of buildings has led to buildings that are increasingly insulated against heat losses. It has been emphasized in many publications and studies that buildings consume around 40% of overall energy used globally. Therefore cutting the energy used by buildings is of major interest in this study. The solar gains in the buildings are twofold. The glazed areas in the new office buildings are getting larger, which increases solar gains during the cold periods of year, however during the warmer season the over-glazed areas can cause overheating problems. Using energy to remove excessive heat is costly and may completely wash out the energy saving effect of utilizing solar energy for space heating. In addition, the solar gains in newly built buildings are considered as significant source of heating. Therefore, the solar gains have to be taken into the total energy demand of a building (EPBD, 2002). Hence, transparent parts of the building envelopes serve several functions. First, they must provide enough light transmittance, or daylight utilization. Second, they should provide sufficient solar energy transmittance during cold months. Third, they should prevent indoor space from overheating during warmer months without blocking the view and the solar energy gains, as has been a pitfall of current shading systems.Since a significant portion of energy in the buildings is devoted to electric lighting and ventilation, daylight and cooling have a large energy saving potential for advanced solar shading systems (Lee, 2009).

BACKGROUND

Based on previous studies, a shading system with light redirecting glass lamellas with a solar control surface was built as demonstration(Laustsen et al., 2008; Iversen et al., 2009). This paper evaluates its performance by conducting simulations. The system removes the drawback of the current shading systems, which partly block views while shading excessive solar gains and redirecting daylight into the back of deep office rooms where daylight is desirable. The investigation was based on the full-scale demonstration project and is accompanied by computer modelling. The purpose of the simulations is to verify the effects of improving daylight conditions and the thermal indoor environment, while ensuring energy savings. The evaluation the performances of the shading system by simulations is the research objective and the central point of the investigation. The investigated simulation model can be used for various buildings, since it is not feasible to build physical demonstrations for all possible building shading scenarios and building layouts. The main focuses are to evaluate the visual performance of the demonstrated system, comparing it with the original system and to compare it with data obtained from the measurements.

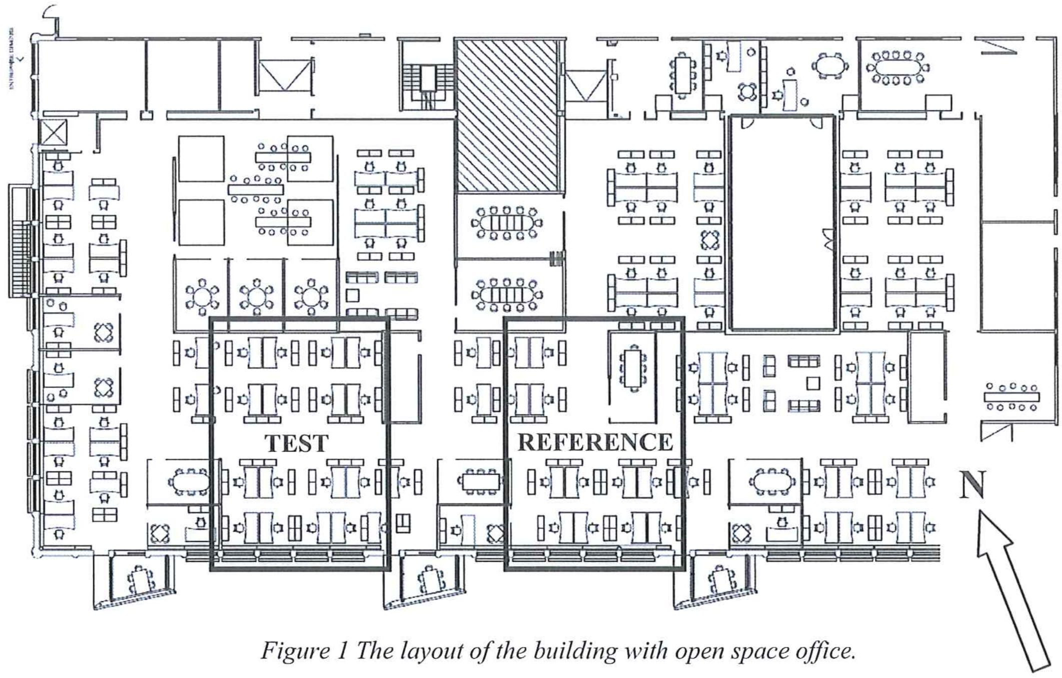

Figure 1 The layout of the building with open space office.

EXPERIMENT

Demonstration building

The demonstration building equipped with a prototype of an external dynamic integrated shading and light redirecting system is located in Humlebaek 30km north of Copenhagen, Denmark (55.96N - 12.49E). The building was refurbished from a production facility to an open space office, which caused deep open space with working spaces far away from the façade. The building is one floor high and the open façade with 2.26m high windows is oriented 11° west by south. The whole building has dimensions of 66m x 28m with longer side oriented south. The surrounded landscape is relatively flat without any big trees or high buildings that might shade the investigated façade. However, the opposite building blocks the open horizon. The open space office has a room depth up to 14m. The floor plan of building is on Figure 1. The building/façade layout allows preservation of a reference office space with the same orientation and similar layout as the investigated space for comparison of daylighting conditions. The two spaces were fitted with same set of illuminance sensors to monitor the actual conditions. The open space is divided by small meeting rooms, which are separated by the partitions. The partitions are partially from wood and glass, which allow better penetration of light into the space. The test and reference areas are both approximately 9.5m wide and 14m deep with ceiling height of 3.45m. The building has windows on the south and west façades with columns between individual windows. The window openings are 1.98m wide and 2.26m high with windowsill 0.75m above the floor. The surface reflectance properties in the building and outdoor were measured by illuminance meter in order to have identical surface properties for the measurements and simulation model. The visible reflectance measurements were averaged from three values measured on different places of the surface (Table 1). The roughness and specularity of surfaces for the model were neglected.

Table 1
Building model surface reflectance values

SURFACE	VISIBLE REFLECTANCE (R_{vis})
Floor	20.5%
White walls	89.3%
Wooden partitions	32.6%
Ceiling	89.9%

The shading system

The major difference between the new and original shading system is that newly installed lamellas rotate in an opposite way, compared to the conventional shading system. The outer edge moves upwards and the upper surface goes towards the façade when the system is closing.

Each window consist of eight lamellas in vertical direction and each lamella is 330mm wide. The rotation directions of the lamellas is demonstrated on Figure 2. Four uppermost lamellas rotated in toward the façade and the rest of lamellas rotate in opposite direction out of the facade. This strategy allows the upper part of the system to redirect and shade while the lower part acts as a traditional shading system which allows to see out. The new system is made from highly reflective solar control coated glass to redirect daylight into the back of the room. New lamellas are produced by Saint Gobain Glass (SGG) and the used glass is Antelio Silver 10mm, with light reflectance of 31%. The original lamellas were made from Parasol Green 8mm with light reflection of 6%, made by SGG, with white frit covering 55% of the surface. The properties of shading glass, glazings and glass partitions are in Table 2.

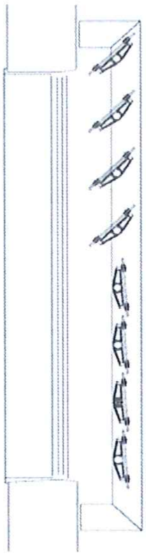

Figure 2 Illustration of the position and rotation angle range for the shading system.

Table 2
Centre-of-glass properties of glass used in the model

GLASS	VIS. TRANSMITTANCE (T_{vis})
Glazing	73%
Glass partitions	88%
New glass lamellas	66%
Old glass lamellas	68% (without frit)

Shading control strategy

The shading strategy of the system was based on results from previous investigation, location and sun position. The most effective daylight redirecting position is when the lamellas are in the position of 30° towards the façade (Laustsen et al., 2008). The lamellas stay in this position when the sky is overcast or the total horizontal illuminance is lower than threshold of 25kLux for longer than 10min. The time delay prevents excessive opening and closing the shading system, which could irritate space occupants. The threshold for moving lamellas back to the redirecting stage, the daylighting conditions are poor was set to 17.5 klux with time offset of at least 20min. This assumption was based on the illuminance under clear, overcast and intermediate sky. The redirecting position was 30° all year around expect May and June when the position was set to 25° down towards the facade. The system had three possible positions:

- Redirecting position 30° (25°)
- Open position 0°
- Close position 90°

In addition, the redirecting position was designed to avoid reflection of direct sunlight from the lamellas surfaces when the sun is partially behind clouds. Hence the space occupants were not exposed to the reflections from and between lamellas. The lowest rotating lamella (fourth from top) was approximately 2m above the floor and therefore it did not interface directly with view out when in redirecting position.

Modelling

To overcome the lack of standardized simulation tools to test the performances of unique shading and redirecting system the state-of-the-art software Radiance was used (Ward et al., 1998). It is generally complicated to simulate effect of reflective surfaces. Therefore, Radiance was utilized for the investigation to depict the transparent properties of the façade and its effect on the indoor environment. Radiance is an accurate backward ray-tracing program which has been extensively validated over past two decades by comparison with measurements and calculation tools. Radiance is capable of simulating illuminance and luminance distribution in complex spaces with diffuse, specular and transparent materials.
Furthermore, to illustrate the potential advantages and disadvantages the tested system was compared with reference case, which is an identical building with the original shading system.

Annual simulations

The comparison between two cases was based on illuminance on a working plane. There are several thresholds, standards, and design recommendations described in literature. The simulated working plane illuminance was derived from test and reference case to find the impact of new system. Several thresholds for working plane illuminance were observed and cumulated over whole year and evaluated by daylight autonomy (DA) and useful daylight illuminance (UDI) matrix, which are explained in detail in next section (Nabil et al., 2005; Reinhart et al., 2011; Mardaljevic, 2000; McNeil, 2010; CEN, 2007).

- 100 lux – Are considered as insufficient for performing tasks under daylighting conditions. It is lower limit for UDI.
- 300 lux – Illuminance around 300 lux is considered as effective for task light source with or without additional artificial light.
- 500 lux – Are described as minimal working illuminance on working space in the office, either with or without artificial light. It is used as threshold for DA analysis.
- 1000 lux – Values around 1000 lux are often described as most desirable illuminance.
- 2000 lux – Illuminace over this value is considered to be discomfortable and may

cause glare problems as well as overheating. It sets upper threshold for UDI.

The recent development of Radiance allowed for annually based simulations by using the program **"rtcontrib"** (Ward, 2005). The geometric model of the building, surroundings and detailed model of the fenestration system was created using the program SketchUp and converted to the Radiance format. The placement of windows on the facade created an almost-continuous band of glazing. Therefore, sensors which are equidistant from the façade could be considered to have same illuminance. The study investigated a row of illuminance sensors perpendicular to the facade with spacing of 0.25m starting 0.5m from the facade in the high of working plan of 0.85m. Other sensors were in the position of the physical illuminance sensors used for the measurements. They were on the working plane and under the ceiling facing a floor to monitor reflected light to the ceiling. The spacing of sensors on the working plane was 0.5m, 3.6m and 8.5m from the facade and 1.5m, 3.3m, 5.1m and 6.9m from the facade under the ceiling.

Daylight Simulation

To calculate the annual illuminance on working plane the three-phase method using Radiance was used (Ward et al., 2011). This method use Radiance tool rtcontrib to generate a matrix form result and separate the results into three independent matrixes for the transmission of fenestration system matrix (XML), exterior daylighting matrix (DMX) and interior view matrix (VMX). This approach allows us to quickly generate different situations for various fenestration systems, locations and sky conditions. The combination can be generated without repeatedly performing whole simulations. This approach is suitable for annual simulation where the sky for every hour is unique. The last information needed for multiplication of matrices is the sky vector, which describes a sky distribution. The sky vector is generated by the Radiance program gendaylit from test reference year (TRY) weather file for Copenhagen (DOE, 2011), Denmark. The sky model uses the Perez sky (Perez et al, 1993; Nabil, 2005), which is generated from the direct normal irradiance and horizontal diffuse irradiance. The sky was divided into 2305 patches according to the Rainhart subdivision for precise results. By multiplying matrixes, the total illuminance in the sensors from all sources in the model is calculated. The transmission matrices were generated by the Radiance program genBSDF which generates a bidirectional scattering distribution function (BSDF) for given fenestration geometry. 145 Klems hemispherical directions were used on each of the sites of the fenestration layer to generate the transmission matrix.

A percentage of the working hours satisfying the daylighting conditions annually were accounted. When the minimum light threshold is not reached the artificial lighting could be add and the artificial light energy saving is equal to the amount of daylight.

Annual daylighting simulation is referred under name several resources as dynamic daylighting simulation, which is conducted in several steps in agreement with three-phase method (Jacobs, 2010; Ward et al., 2011).

1. Sky model with irradiance/illuminance data.
2. Time steps within the working hours.
3. Radiance simulation for each time step and each sensor position or rendering, i.e. view, daylighting and transmission matrix combination.
4. Asses how many times the required designed working illuminance is satisfied (or partly satisfied).
5. Count how much artificial light is needed to add to satisfied minimal working plane illuminance.

The Radiance simulation parameters for generating VMX, XML, DMX matrix are listed in Table 3.

Table 3
Radiance parameters for matrixes

RADIANCE SIMULATIN PARAMTER	VMX	XML	DMX
ambient bounces (-ab)	6	3	6
Ambient divisions (-ad)	2048	350	10000
limit weight (-lw)	1.00E-12	0.0001 (-st)	1.00E-3
direct source subdivisions (-ds)	0.1	0.2	0.1

Daylight factor (DF) was not used for investigation the daylighting conditions in the room because it does not quantify the redistribution of the direct beam of the radiation to provide diffuse illuminance in the indoor space, which is the main feature of the daylight redirecting shading system. Furthermore, the building location and orientation is not taken into account in DF concept.

The annual illuminance matrix provides information need to evaluate the daylighting conditions in the interior. The most commonly used daylight performance matrices nowadays, except DF, are useful daylight illuminance (UDI) and daylight autonomy (DA) (Mardaljevic, 2005; Nabi et al., 2005; McNeal et al., 2010; Reinhart et al., 2011).

DA is the percentage of hours which satisfy the minimal designed working plane illuminance from the total number of working hours in a year. The criteria for minimal illuminance according to ISO standard is 500 lux (CEN, 2007). The UDI matrix quantifies when the daylight is perceived as useful for occupants of the space. It is calculated as percentage of the occupancy working hours when the illuminace on the working plan is between the threshold of 100 lux and 2000 lux.

DISCUSSION AND RESULT ANALYSIS

Comparison of radiance and measurements results

The placement of the measurement sensors was caused to be minimally blocked. The space was modelled without furniture which was comparable with the measurements because the sensors had free view to the façade and provided comparable resuts. The reason for removing the furniture from simulations was that furniture was not fixed and it was hard to assume where it would be at the time of the measurements.
Additionally it was not possible to observe position of the lamellas during whole time of measurements as well as interior shadings position, curtain and venetian blinds, which were operated manually. For those reasons errors between simulation and measurements could occur. The compared illuminance sensor laid 3.6m away from the window, which is approximately in the position where the daylighting conditions could be already improved. Sensors closer to the window were exposed to the high level of illuminance and could have a high error and the sensors deeper in the room had higher probability of being shaded. The two curves on Figure 3 present the values for Radiance simulation and measurements for a sunny day. To have as similar of conditions as possible, a day without occupancy was simulated. Additionally a sunny day was selected because it sky distributions for sunny skies can be generated more accurately with the Radiance program gensky. The day chosen was Sunday, September 5, 2010. The scattered data on right are common for both cases and were caused by the light coming through the building from the west facade, which indicates that the model is providing comparable data to the measurements. The peak in the morning in the simulations is not common with measured data and it was probably caused by the unknown position of the internal shades.

Daylight autonomy

Figure 4 and Figure 5 present the situation when the shading system was in the shading position, closed. This position was common for both test and reference case and therefore could be comparable. Higher percentage of the hours over the observed illuminance thresholds was reached in the deeper distance from the facade and DA was satisfied more often. The threshold of 500 lux was reached at least 50% of all the working hours at a distance of 4.5m for the tested system compared to approximately 3.2m for the original system. In the distance of 4m from facade in the tested situation around 55% of time reached at least 500 lux on the working plane whilst for the reference shading it was around 45%. The improvement of the daylight conditions is visible all over the depth the investigated space. Furthermore, the room depth when the threshold of 300 lux was almost never reached moved from 8m to 10m from the facade, which covers most of the working area in the office space. However, DA does not penalize excessive illuminance which could be reason for glare problems and therefore UDI matrix was calculated too.

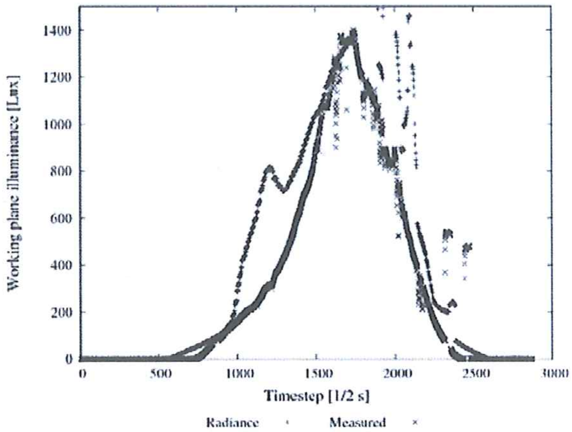

Figure 3 Comparison of measured and Radaince illuminance in sensor 2

Useful daylight illuminance

The excessive working plane illuminance is present for both cases and in every investigate position of the shading system as it is in Figure 6. The depth of the room with illuminance higher than 2000 lux shifted in average approximately 1m into the room, which is not a significant downgrade. Nevertheless, the time when the places could be exposed to the higher illuminance increased by tenths of percents. However most of the working places are out of this highly illuminated zone and in both cases a glare occur. Hence the internal shades would have to be closed when there is excessive illuminance.
More importantly, the situation with insufficiently low daylighting condition in the evaluated space was limit. The illuminated zone with sufficient daylight is bigger with tested system than with the original. The daylight redirecting position of the lamellas further increase the zone lit by the daylight.

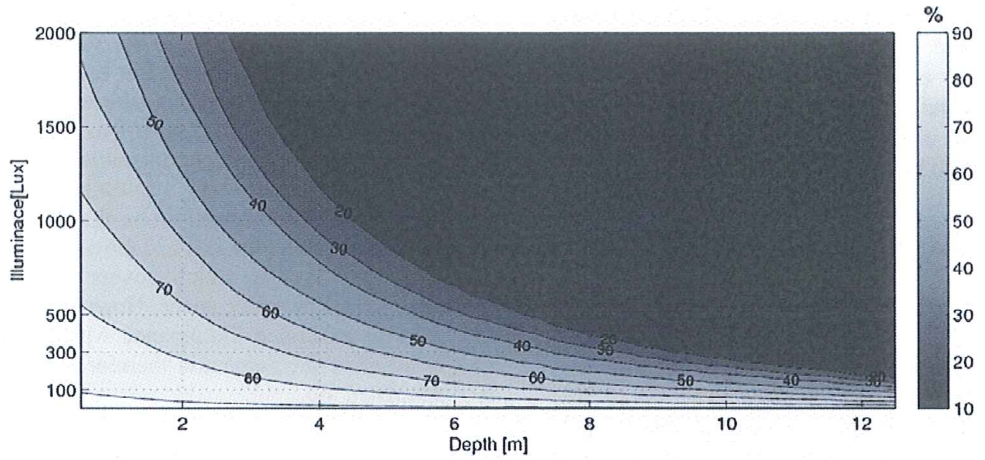

Figure 4 Daylight autonomy of the tested shading system in the closed position

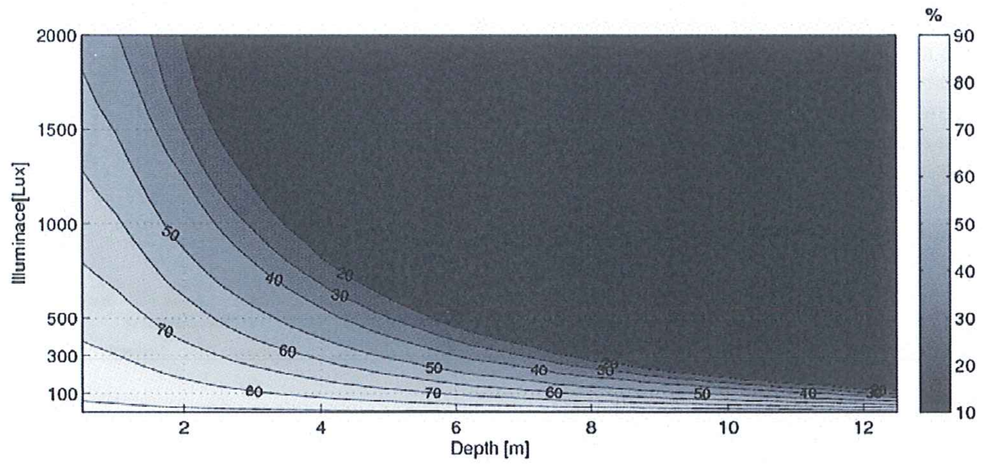

Figure 5 Daylight autonomy of the original shading system in the closed position

Further work

Apart from performing the visual daylighting analysis, the further work on the evaluation of this system should include more in depth glare analysis with focus on the visual zone of the occupants and annual evaluation (Wienold, 2009). Moreover, we will evaluate the changes to total energy consumption from both artificial lighting reductions. The solar gains for heating during the winter should be evaluated, since it is considered as source of energy for the low energy buildings as well as buildings in the Nordic countries.

CONCLUSION

This paper evaluates a prototype dynamic integrated shading and light redirecting system designed to optimize daylight conditions in an office building and a control of solar gains whilst a quality of indoor environment and view out is preserved and improved. Part of an existing façade with glass lamellas in Humlebaek, Denmark was rebuilt to test and further develop the prototype of the concept. The building façade also has a reference office

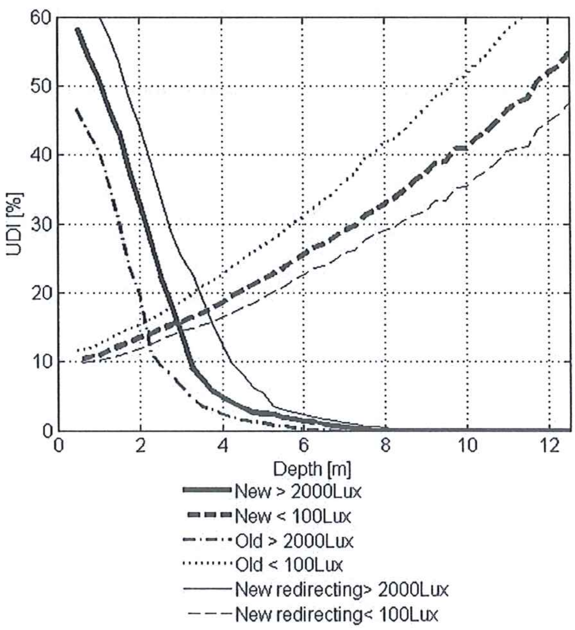

Figure 6 Annual useful daylight illuminance matrix for different scenarios.

space with the same orientation and layout as a reference for comparison of investigated parameters from measurements. The automated external glass lamellas were synchronized with the actual sky and sun distribution to expand the zone with the designed workspace illuminance lit by daylight, reduce overheating and maximize view out.

In this study, the lighting conditions were simulated and measured during summer and autumn weather conditions. A daylight improvement was achieved with the redirecting glass lamellas shading system compared to the existing shading system in the building.

ACKNOWLEDGEMENTS

The research performed in this study was funded by the Danish Energy Agency programme for research and development of energy efficiency, PSO - F&U 2008.

REFERENCES

CEN - EN 15251, 2007, Indoor environment input for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lightning and acoustics.

DOE, 2011, United States Department of Energy, Weather data, Internet, http://apps1.eere.energy.gov/buildings/energyplus/weatherdata/6_europe_wmo_region_6/DNK_Copenhagen.061800_IWEC.zip, May 2011.

EN 15251, 2007. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.

EPBD, 2002, European Directive on the Energy Performance of Buildings (2002). Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the Energy Performance of Buildings

Iversen, A.; Laustsen J.B.; Svendsen, S.; Traberg-Borup, S.; Johnsen, J., 2009. Udvikling af nye typer solafskærmnings-systemer baseret på dagslysdirigerende solafskærmende glaslameller, Lyngby, Denmark.

Jacobs A. 2010. Understanding rtcontrib, London, UK.

Laustsen, J. B.; Santos, I. D. P.; Svendsen, S.; Traberg-Borup, S.; Johnsen, K., 2008, Solar Shading System Based on Daylight Directing Glass Lamellas, Building Physics 2008 - 8th Nordic Symposium

Lee E.; 2009. Advanced High-Performance Commercial Building Facades Research, LBNL, Berkeley, USA – presentation

Mardaljevic, J.; 2000. Daylight simulation: validation, sky models and daylight coeffcients. PhD thesis. Leicester: De Montfort University.

McNeil, A.; Lee, E.S. 2010. Annual Assessment of an Optically-Complex Daylighting System Using Biderectional Scattering Distribution Function with Radiance, DEO/LBNL FY10 Technical Report Deliverable, Berkeley, California, USA – under review.

Nabil, A.; Mardaljevic, J. 2005. Useful daylight illuminance: a new paradigm for assessing daylight in buildings, Lighting Res. Technol., 37 (1) pp. 41-59.

Perez R.; Seals R.; Michalsky J.; 1993.All-weather model for sky luminance distribution-preliminary configuration and validation. Solar Energy, 50(3), 235-245.

Reinhart, C.F., Wienold, J. 2011. A simulation-based analysis for daylit spaces, Building and Environment 46, pp. 386-396.

Ward G., 2005. Radiance's new rtcontrib program, 4rd Internatiol Radiance Workshop Montreal, Canada.

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, Berkeley, USA - accepted for publication in Leukos, Journal of the Illuminating

Ward G., 2005. Radiance's new rtcontrib program, 4rd Internatiol Radiance Workshop Montreal, Canada.

Ward, G.; Shakespeare, R.A., 1998. Rendering with Radiance, published by Space & Light, Davis, California, USA.

Wienold J. 2009. Dynamic Daylight Glare Evaluation, Building Simulation 2009, Glasgow, Scotland.