Comparing the accuracy of daylighting physical and virtual models for complex fenestration systems

A. Thanachareonkit, J.-L. Scartezzini and D. Robinson

Solar Energy and Building Physics Laboratory (LESO-PB)
Ecole Polytechnique Fédérale de Lausanne (EPFL), CH – 1015 Lausanne, Switzerland

ABSTRACT: Nowadays, many new window components known as complex fenestration systems (CFS), such as laser-cut panels and prismatic films, are considered in order to improve the overall luminous properties of building spaces : detailed studies of CFS remain necessary however to validate their daylighting performance. Physical and virtual models are commonly used to assess the daylighting performance of more conventional daylighting strategies within buildings. Several recent studies have reported significant errors for both physical and virtual modelling procedures, 10% modelling errors leading in both cases up to 30 % inaccuracy in daylight factors assessment: no similar error analysis was carried out in a systematic way for daylighting strategies involving CFS use. A side lit office room equipped with double glazing and a CFS (laser-cut panel and prismatic film) was mocked-up for that purpose in a daylighting test module. The office room was reproduced by way of a 1:10 scale physical model placed under a scanning sky simulator, as well as a virtual model built-up by the way of Radiance lighting program. Several model parameters were varied, leading to the evaluation of model inaccuracies through a sensitivity analysis. The most significant factor (internal surface reflectance) is considered in this paper, leading to a first set of modeling guidelines.

Keywords: Complex fenestration systems, daylight factor, work plane illuminance, scale models, virtual models, sources of errors.

1. INTRODUCTION

Physical and virtual models of buildings are commonly used to assess their daylighting performance (e.g. daylight factors). Several authors [1], [2], [3], [4] have however reported that both lead to significant errors when comparing the predicted performance with the daylight factors monitored in real buildings. Inappropriate matching of indoor surface reflectance and window transmittance of scale models with the real building values is responsible for a large range of discrepancies, even in case of conventional dayligthing strategies (e.g. side lit window) [5]. Allowing enough time and effort to mock-up these features is believed to be the only way to reduce the frequently observed overestimation of daylight factors within scale models [6].

In order to carry out an in-depth analysis of the sources of errors in the daylighting performance assessment of buildings equipped with Complex Fenestration Systems (CFS), physical and virtual models of a given office room were compared under the same lighting conditions. This work follows a previous study [6], which considered a side lit office space (a 1:1 test module) and its physical model (a 1:10 scale model), for which photometric properties of materials (transmittance and reflectance), as well as the response features of illluminance sensors, were carefully examined. A virtual model of the same side lit office space, was set using the well-known Radiance lighting programme [7]. Complex fenestration systems (laser cut panel, prismatic film) were added both to the physical and virtual models in order to identify the main error sources for these more advanced daylighting strategies. Figure 1 illustrates the overall procedure, employed to achieve the corresponding sensitivity analysis by considering both modeling techniques.

2. DESCRIPTION OF MODELS

2.1 Physical model

A physical model of the mocked-up office room (the full scale room is shown in Figure 2) was built using synthetic foam sandwich cardboards. Table 1 presents the features corresponding to the full-scale test module and its 1:10 scale model. A particular emphasis was placed on the modelling of the reflectance properties of the internal module surfaces, which were identified previously as the main error sources during daylighting performance assessment [6]. A southern oriented side window (double glazing, 4/12/4 mm) and two different CFS [8] (cf. Figure 3) were considered. The laser cut panel (LCP) is made of a 6mm thick acrylic pane with 4 mm-spaced parallel laser cuts. The prismatic film, made of polycarbonate, shows parallel structures. The two are illustrated in Figure 4. Both CFSs used in the scale model are not scaled down due to model construction limitations. In all other respects the two models are essentially identical.

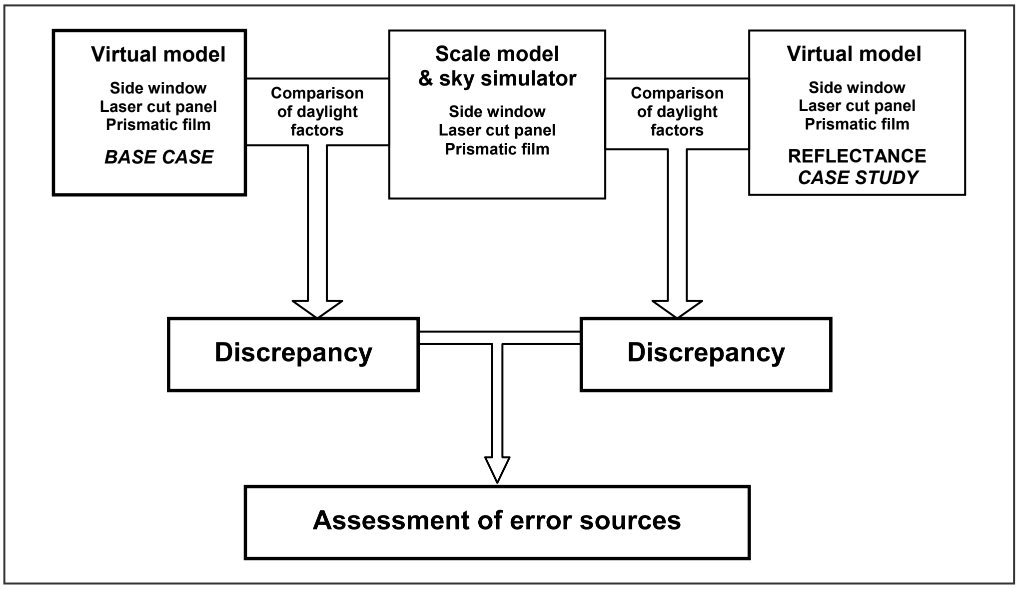

Figure 1: Overall procedure used to identify the main error sources of physical and virtual daylighting models.

Figure 2: (Left) Scale model under scanning sky simulator; (Right) Full-scale test module on EPFL campus.

Figure 3: Glazing systems mock-up used on 1:10 scale model; (Left) 2mm.-single clear acrylic foil with neutral filter; (Middle) laser cut panel and (Right) 3M prismatic film.

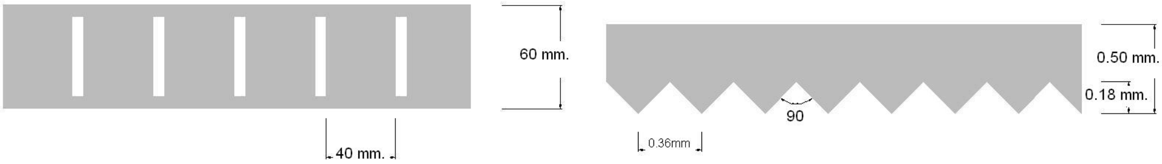

Figure 4: Transversal section of Laser Cut panel (Left) and 3M prismatic film (Right) placed on 1:10 scale model.

2.2 Virtual model

The virtual model was carefully designed to match exactly the geometrical and photometrical features of the 1:10 scale model (cf. Table 1). External sources of errors regarding the computer simulation parameters were not expected for this reason. The scale model was placed under a scanning sky simulator reproducing accurately a CIE standard overcast sky (cf. Figure 2); the same sky luminance distribution was assumed for all computer simulations, including the “Base case”.

A sensitivity analysis of surface reflectance was carried out both for models including a side window as well as different CFS : surface reflectance values ranging from 0.1 x $\rho_{\text{Base case}}$ to 1.5 x $\rho_{\text{Base case}}$ for the floor, limited upward to 1.1 x $\rho_{\text{Base case}}$ for the walls and ceiling, were considered for that purpose. Daylight factor profiles, observed in the models at 7 different locations separated by 0.1m distances, were compared as stated in Figure 1. The relative divergence observed between daylight factors were used to quantify the impact of surface reflectance on the virtual model accuracy.

Description		Test module	1:10 Scale model	Virtual model (Base case)
Geometry	**Length (m)**	6.5 ± 0.1	0.650 ± 0.005	6.5
	Width (m)	3.0 ± 0.1	0.300 ± 0.005	3.0
	Height (m)	2.5 ± 0.1	0.250 ± 0.005	2.5
	Facade area (m2)	7.5 ± 0.2	0.0750 ± 0.01	7.5
	Glazed area (m2)	3.6 ± 0.2	0.036 ± 0.01	3.68
	Occupants (-)	0	0	0
Fenestration materials	**Side Window**	Double glazing	2 mm.-Single acrylic w/ neutral filter film	Window function
	Laser Cut Panel	6 mm-Single acrylic w/ 4 mm parallel cuts	6 mm-Single acrylic w/ 4 mm parallel cuts	BTDF Data
	Prismatic film	3M Brand optical lighting film (90° micro-prisms)	3M Brand optical lighting film (90° micro-prisms)	BTDF Data
Indoor surface materials	**Floor**	Fitted carpet (Green)	Paper (Textured Green)	-
	East wall	Satin (White)	Paper (White)	-
	West wall	Satin (White)	Paper (White)	-
	North wall	Canvas (White)	Paper (White)	-
	Ceiling	Satin (White)	Paper (White)	-
	South wall	Painted metal (White)	Paper (White)	-
Reflectance (%)	**Floor**	16.1 ± 0.9	16.4 ± 0.2	16.4
	East wall	81.5 ± 0.3	79.4 ± 0.1	79.4
	West wall	82.3 ± 0.4	79.3 ± 0.1	79.3
	North wall	72.1 ± 0.4	70.8 ± 0.1	70.8
	Ceiling	79.9 ± 0.2	76.0 ± 0.1	76.0
	South wall	82.6 ± 0.4	79.1 ± 0.1	79.1
Transmittance (%)	**Side Window**	80.5 ± 0.1	79.2 ± 0.1	79.2
Radiance Simulation Parameters *	**ab**	-	-	9
	aa	-	-	0.3
	ad	-	-	26315
	ar	-	-	8

Table 1: Geometrical and photometrical features of the test module, 1:10 scale model and virtual model.

* aa: ambient accuracy - value approximately equal to the error for indirect illuminance interpolation, ab: ambient bounces - maximum number of diffuse bounces computed by the indirect calculation, ad: ambient divisions - error in the Monte Carlo calculation of indirect illuminance, ar: ambient resolution - number determining the maximum density of ambient values used for the interpolation. [7]

3. COMPARISON OF MODELS ACCURACY

Under CIE overcast sky the virtual “Base case” and the scale model, both equipped with a conventional side window, led to a minimal relative divergence of 1%, at distance of 1.2m along the centerline from the window and a height of 0.74 m, and 9.2% maximal relative divergence at 2.2 m (cf. Figure 5). The average relative divergence over the whole daylight factor profile is equal to 4.9%, confirming the excellent accuracy of the Radiance lighting program.

When attaching a laser cut panel to the window, the relative divergence led to a minimum of 0.5% at 6.2 m window distance and a maximum of 16% at 3.2 m (cf. Figure 6); the average relative divergence is equal to 11.3% over the whole profile. Combining a prismatic film to the window led to a minimal discrepancy of 2.2% at 4.2 m from window and a maximal relative divergence of 35.7% at 2.2 m distance from window (cf. Figure 7); the average relative divergence in this case is equal to 16.1%.

Complex fenestration systems are difficult to model, both numerically and physically. The use of BTDF data, measured using a bidirectional goniophotometer [9], represents a good approach to solving numerical difficulties, but they remain scaling problems that are difficult to resolve in physical modeling. For these reasons there remain some significant divergences between the two approaches.

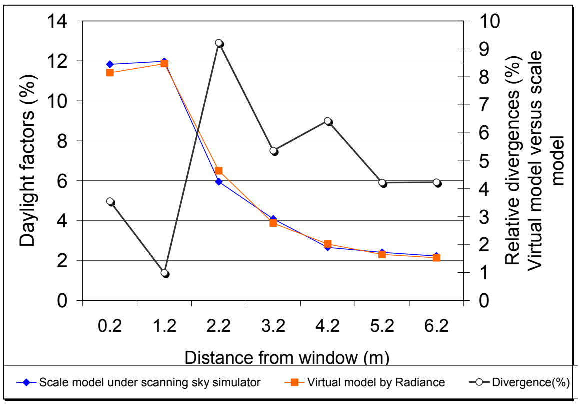

Figure 5: Comparison of daylight factors observed in the scale model and calculated with the virtual model for "Base case" (Side window).

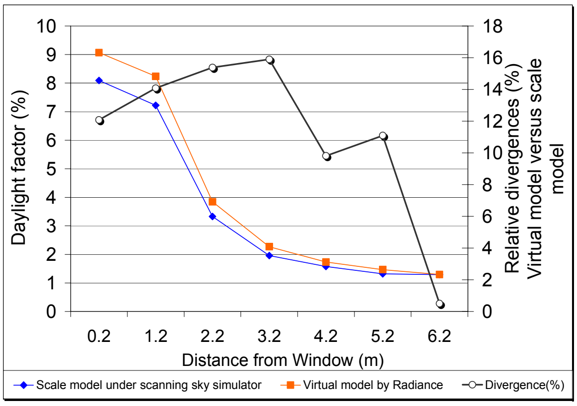

Figure 6: Comparison of daylight factors observed in the scale model and calculated with the virtual model for "Base case" (Laser cut panel).

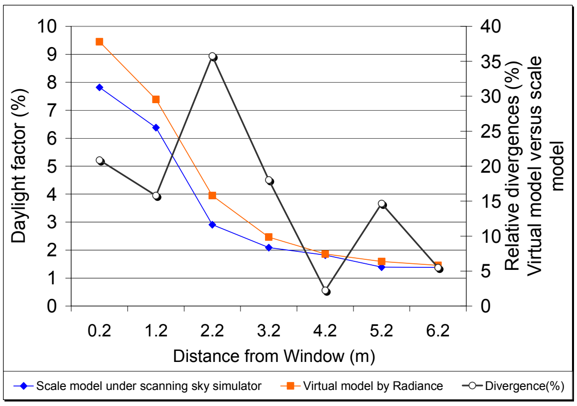

Figure 7: Comparison of daylight factors observed in the scale model and calculated with the virtual model for "Base case" (Prismatic film).

The sensitivity analysis, performed by assuming surface reflectance equal to values 90% lower and 50% larger (walls and ceiling only 10% larger) than the scale model corresponding $\rho_{\text{Base case}}$ values, led to larger relative divergences.

For the virtual model with side window, the average discrepancy reached - 17.2% for a 10% reduction of surface reflectance and + 52% for a 50% overestimation of surface reflectance (walls and ceiling only 10% larger), as shown by Figure 9.

For the virtual model with laser cut panel, the average discrepancy reached - 17 % for a 10% reflectance reduction and + 65% for a 50% reflectance overestimation (walls and ceiling only 10% larger), as shown by Figure 10. Larger figures were also observed for the prismatic film, when comparing to the virtual model "Base case" (cf. Figures 5 to 7), the average discrepancy reaching - 27 % for a 10% reflectance reduction and + 78% for a 50% reflectance overestimation (walls and ceiling only 10% larger), as shown by Figure 11.

Surface reflectance remains as a consequence an important parameter regarding the virtual models accuracy, particularly for position deeper within the room, for which internally reflected light tends to dominate. The complexity of light propagation through CFS being accounted for by the integration of monitored BTDF data into the Radiance program [10], discrepancies remains however reasonable compared to a simple daylighting strategy like a side window.

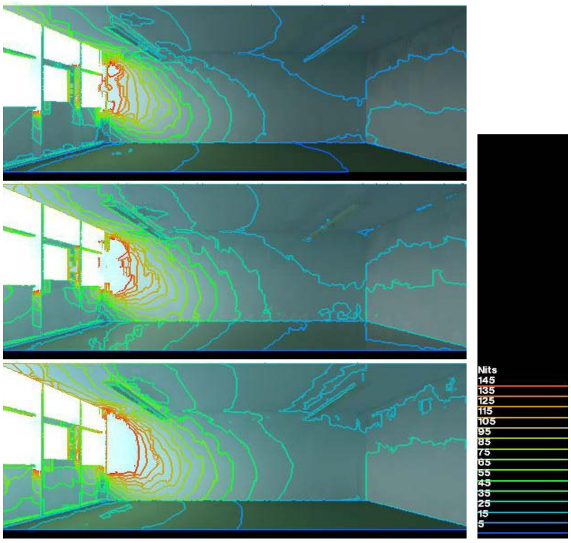

Figure 8: Virtual model rendering for three different reflectance (0.9, 1.0 and 1.1 x $\rho_{\text{Base case}}$).

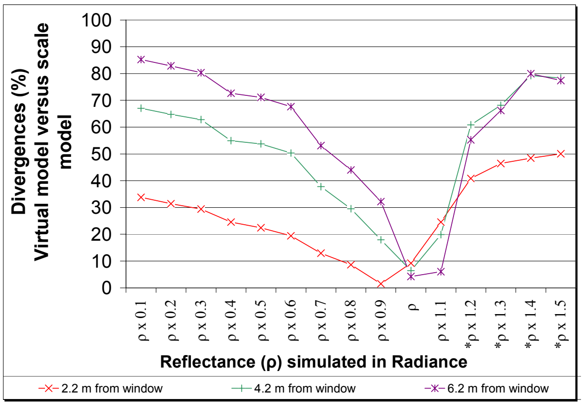

Figure 9: Sensitivity analysis of surface reflectance of virtual model (Side window). *Walls and ceiling only up to 10% larger than Base case.

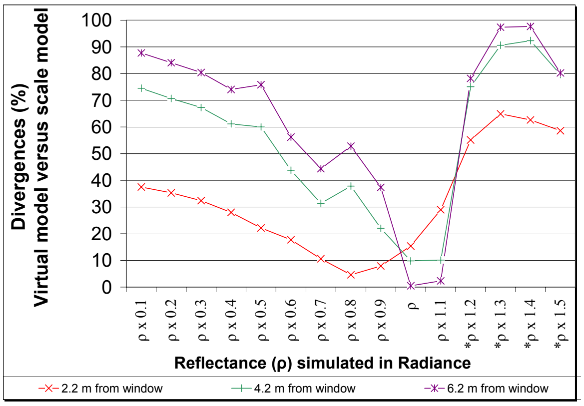

Figure 10: Sensitivity analysis of surface reflectance of virtual model (Laser cut panel). *Walls and ceiling only up to 10% larger than Base case.

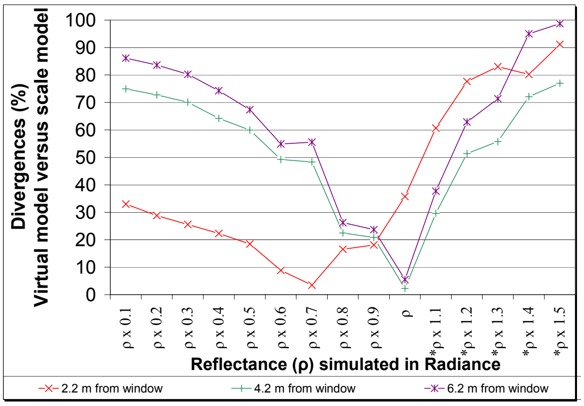

Figure 11: Sensitivity analysis of surface reflectance of virtual model (Prismatic film). *Walls and ceiling only up to 10% larger than Base case.

4. MODELS DESIGN GUIDELINES

In order to facilitate the preparation of models, design rules were drawn from the sensitivity analysis results carried out on the surface reflectance, assuming that the optimal configuration of simulation parameters is achieved by the “Base case”. Figure 12 shows the impact of under- and overestimation of surface reflectance for the case of a side lit office room (double glazing). Larger discrepancies tend to be observed for overestimation of surface reflectance. A 10 – 50% overestimation (i.e. above the “Base case” values) leading to a 5 - 52% relative divergence of daylight factors above the corresponding monitored values (scale model). Underestimation of surface reflectance leads in comparison to lower relative divergence, a similar underestimation range leading to 10 – 40% lower figures. It is interesting that the overestimation is exponential in nature : this can be explained with recall to the Split-flux equation. [11]

Figure 13 shows the comparable values of average relative divergence observed for the virtual model which includes a laser cut panel, both in case of under- and overestimation of the surface reflectance in regard to the “Base case” optimal configuration. Slightly different values were obtained for the virtual model equipped with a prismatic film, as illustrated by Figure 14. Average relative divergence of 5 to 62% above the monitored daylight factors were observed for 10 – 50% overestimation of surface reflectance (walls and ceiling only up to 10% larger), the same range of underestimation of these parameters leading to 5 – 30% lower values.

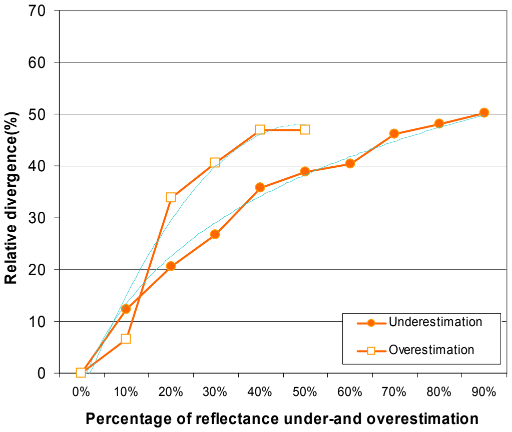

Figure 12: Average relative divergence observed in case of under- and overestimation of the model surface reflectance (Side window).

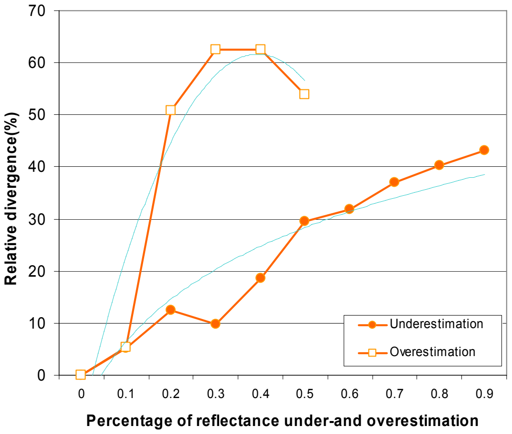

Figure 13: Average relative divergence observed in case of under- and overestimation of the model surface reflectance (Laser Cut panel)

The consistency of these results confirmed the adequacy of the CFS simulation techniques, which uses backward ray-tracing methods in conjunction with BTDF data to handle the complexity of light propagation through these fenestration systems. An extension of the sensitivity analysis to the other model parameters (window transmittance, geometrical features, etc.) should support the preparation of a comprehensive set of modeling guidelines.

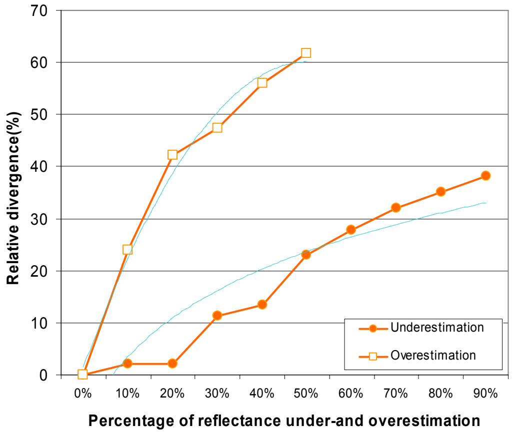

Figure 14: Average relative divergence observed in case of under- and overestimation of the model surface reflectance (Prismatic film).

5. CONCLUSION

This study is aiming toward the identification of the main sources of error in physical and virtual daylight modeling which may lead to an incorrect evaluation of building daylighting performance. It is tackling to the difficulties of modeling Complex Fenestration System (CFS), like laser cut panels and prismatic films, for both models. An appropriate simulation technique for CFS analysis was developed for that purpose, by the integration of monitored BTDF data into the Radiance lighting programme. Based on a sensitivity analysis of surface reflectance, ranges of relative divergence between monitored and predicted daylight factors were obtained. Larger discrepancies in both models occurred when the surface reflectance was overestimated with regard to the real figures. Initial design rules to support practitioners in their building modeling process are proposed; the study is expected to produce a comprehensive set of modeling guidelines.

ACKNOWLEDGEMENTS

This research project is supported by the VELUX Foundation Switzerland. The authors would like also to thank P. Loesch for the model construction assistance, the 3M (Schweiz) AG for Prismatic film, the INGLAS Innovative Glassysteme GmbH & Co. KG for the Laser cut panel, R. Compagnon and J. Kaempf for Radiance simulation assistance, Laurent Michel for Sky scanning simulator calibration, as well as A. Machacek for his help in the model materials selection.

REFERENCES

[1] Schiler, M. (Editor): *Simulating daylight with architectural models*, Daylighting Network of North America, University of Southern California, Los Angeles, 1987.

[2] Love, J. A. and Navvab, M.: Daylighting estimation under real skies: A comparison of full-scale photometry and computer simulation, *J. Illuminating Engineering Society*, 20(1), pp. 140-156, IESNA, USA, 1991.

[3] Cannon-Brookes, S. W. A.: Simple scale models for daylighting design: Analysis of sources of error in illumination prediction, *Lighting Research and Technology*, Vol. 29, pp. 135-142, CIBSE, UK, 1997

[4] Ashmore, J. and Richens, P.: Computer Simulation in Daylight Design: A comparison, *Architectural Sciences Review*, Vol. 44, pp. 33-44, University of Sydney, Australia, 2001.

[5] Thanachareonkit, A., Scartezzini, J.-L., Robinson, D.: Analysis of error sources within daylighting physical and virtual models of buildings, *Proc. of CISBAT 2005 International Conference*, pp. 429 – 435, Lausanne, Switzerland, 2005.

[6] Thanachareonkit, A., Andersen, M. and Scartezzini, J.-L.: Comparing daylighting performance assessment of buildings within scale models and test modules, *Solar Energy*, 73(2), pp. 168 –182, Elsevier Science, UK, 2003.

[7] Ward, G. and Shakespeare, R.: *Rendering with Radiance: The Art and Science of Lighting Visualisation*, Morgan Kaufmann Publications,1997.

[8] International Energy Agency, 2000, *Daylight in Buildings : a Source Book on Daylighting Systems and Components*, Report of IEA Task 31/ECBCS Annex 29, 2000.

[9] Andersen M., Michel L., Roecker C., and Scartezzini J.-L.: Experimental assessment of bidirectional transmission distribution functions using digital imaging techniques, *Energy and Buildings*, 33(5), pp. 417-431, 2001.

[10] Kaempf J. and Scartezzini J.-L.: *Integration of BT(R)DF data into Radiance Lighting simulation programme*, Technical Report, CTI Project 4881.1 "Bidirectional Goniophotometer", 30 p., Solar Energy and Building Physics Laboratory, EPFL, 2004.

[11] Hopkinson R.G., Petherbridge P. and Longmore J.: *Daylighting*, Heinemann, London, 1966.