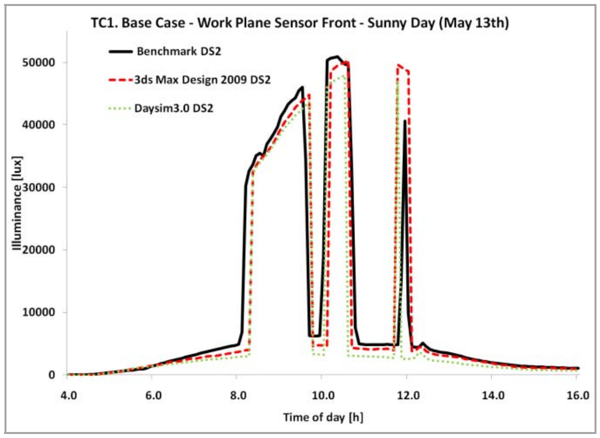


Experimental Validation of 'Autodesk® 3ds Max® Design 2009' and Daysim3.0

NRC Project # B3241

Submitted to:

Ken Pimentel
Autodesk Media and Entertainment
Milford, CT 06460, USA

Submitted by:

Christoph Reinhart[1,2] and Pierre-Felix Breton[3]

1) National Research Council Canada - Institute for Research in Construction (NRC-IRC)
Ottawa, ON K1A 0R6, Canada (2001-2008)

2) Harvard University, Graduate School of Design
Cambridge, MA 02138, USA (2008 -)

3) Autodesk Media and Entertainment
Canada

January 29, 2009

Table of Contents

Experimental Validation of 'Autodesk® 3ds Max® Design 2009' and Daysim3.0

Abstract

This report compares daylight simulation results generated with two simulation programs, 'Autodesk® 3ds Max® Design 2009' (3ds Max Design) and Daysim3.0 (Daysim), to real indoor illuminance measurements in a sidelit space. The sidelit space was in a single location, but was configured with five fenestration and glazing options, and operated under a variety of sky conditions. The measurements form a set of 'daylighting test cases' that were recently developed to evaluate the simulation capabilities and limitations of different daylight simulation programs. Both simulation programs were given external direct and diffuse irradiances as simulation input, from which they had to predict indoor illuminances on a grid of upward facing work plane sensors and downward facing ceiling sensors.

3ds Max Design is based on Exposure™ technology, a lighting analysis module that includes a 'shader' of the Perez sky model and that uses the mental ray® raytracer for the global illumination calculation. Daysim also uses the Perez sky model and is based on the Radiance backward raytracer combined with a daylight coefficient approach. The comparison of both programs with measurements demonstrated that 3ds Max Design simulated indoor illuminances for the daylighting test cases with reliability comparable to Daysim. Most mean bias errors and root mean square errors were in the range of those reported in earlier validation studies: both programs succeeded in reproducing measurements for a sidelit space with and without a lightshelf. While 3ds Max Design consistently underestimated the incoming light flux going through a translucent panel, Daysim results were lower than measurements for the internal venetian blind test case. The results suggest that the accuracy of both programs is sufficient for typical daylighting design investigations of spaces with complexity comparable to the five daylighting test cases.

1 Introduction

The Radiance backward raytracer is a lighting simulation program that was initially developed by Greg Ward in the late eighties at Lawrence Berkeley National Laboratory (Ward and Rubinstein 1988). The program generally enjoys the status of a 'gold standard' among daylight simulation programs as manifested e.g. in a 2006 survey of close to two hundred daylighting modelers from twenty-seven countries who expressed a strong bias towards Radiance. The survey participants named over forty different software packages that they frequently used but over 50% of all votes went to tools that are based on Radiance[1] (Reinhart and Fitz 2006). What are the reasons for Radiance' reputation? Commonly quoted qualities of Radiance are its flexibility, that it is 'physically based', and its capability to simulate complex geometries with various reflection and transmittance material properties. But, other raytracing programs offer comparable flexibility. So, one might conclude that Radiance's reputation is partly founded on a series of independent validation studies that investigated how closely

[1] A caveat of the study – as stated by the authors – is that invitations to participate in the survey (although they were disseminated as widely as possible) were somewhat skewed towards Radiance users due to the simple fact that the authors are part of that community and therefore yielded a high feedback rate on the survey.

Radiance simulation predictions approached physical measurements under thousands of sky conditions in full-scale spaces with either a clear glazing and a lightshelf (Mardaljevic 1995; Jarvis and Donn 1997), venetian blinds (Reinhart and Walkenhorst 2001), or a translucent glazing (Reinhart and Andersen 2006). For a detailed discussion of these validation studies the reader is referred to the Reinhart/Andersen study.

If validation studies based on measured data carry such weight among design practitioners interested in physically based simulation, it initially seems surprising that that there are so few comparable validation studies for other simulation programs available. One could argue that measurement-based validations are expensive. But, the British Building Research Establishment (BRE) has offered a very rich data set of indoor illuminances in a full scale test room for many years (Aizlewood 1993). Surprisingly, to the authors' knowledge, only one researcher has ever used the BRE data set extensively (Mardaljevic 2000). Whatever might be the reasons for the limited use of the BRE data, a new data set has been recently collected in the Daylighting Laboratory of the National Research Council Canada (NRC) in Ottawa (45^{o}N, 76^{o}W). The data set consists of measured indoor and outdoor illuminances as well as direct and diffuse outdoor irradiances for five daylighting test cases of varying complexity. Thousands of measurements under a range of sunny and cloudy sky conditions were collected for each test case. The test cases, schematically shown in Figure 1, are a basic sidelit space with a standard double glazing (TC1), the same space with a diffuse lightshelf (TC2), translucent panels instead of clear glazings (TC3), an external venetian blind (TC4) and an internal venetian blind (TC5). The different elements are increasingly difficult to simulate so that the cases can be grouped into low, intermediate and high complexity.

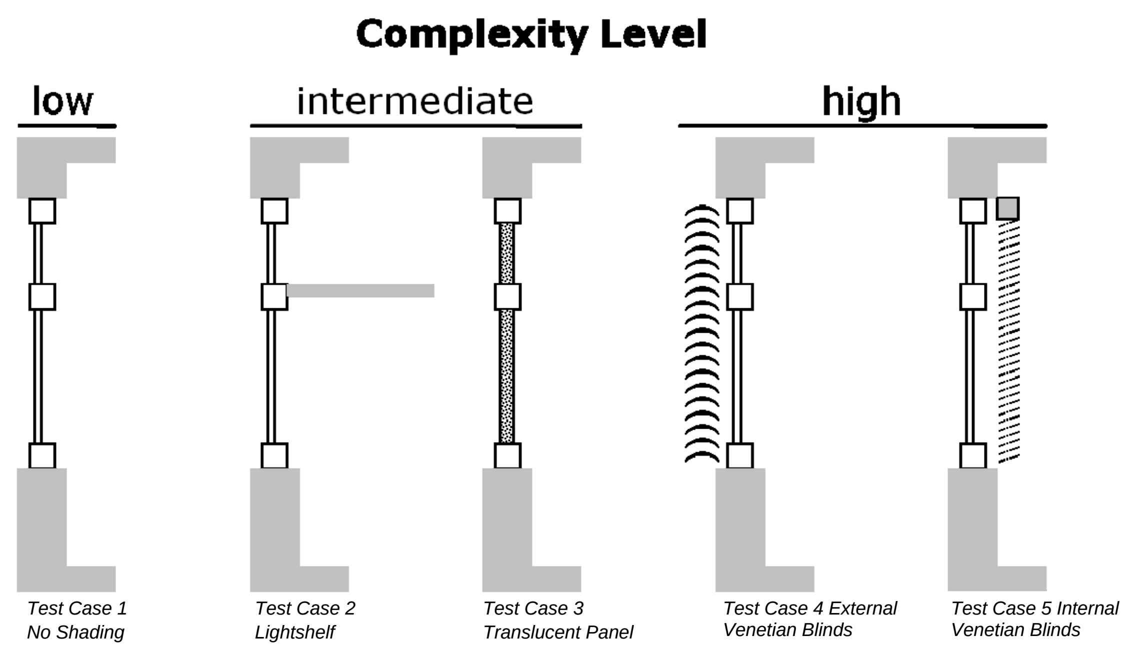


Figure 1: Façade sections of the five NRC daylighting test cases.

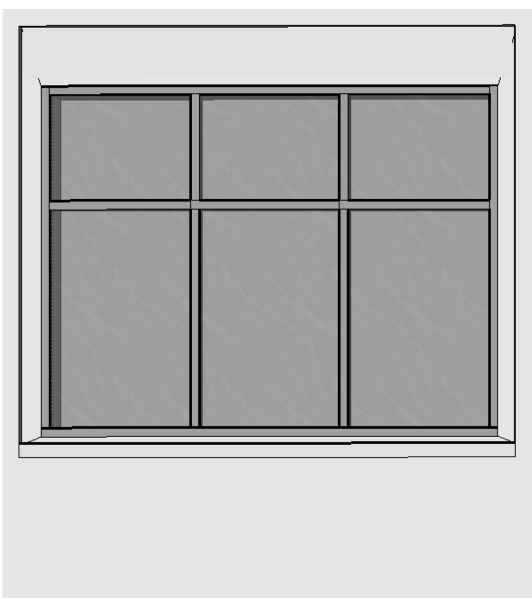
The authors decided to generate this new data set instead of simply using the BRE data for a variety of reasons. First of all the new data set expands the BRE data in the sense that a wider variety of test cases were investigated that are more challenging to model than a clear glazing and a diffuse lightshelf[2]. A larger objective of this work is to promote the use of validation studies among software developers and having its own data set will allow the NRC to further distribute it to other parties. An acknowledged limitation of the new data set is that direct and diffuse irradiances were collected instead of sky luminance distribution. The absence of measured sky luminances limits the evaluator's capability of differentiating between modeling errors introduced by the sky model versus the global illumination engine. On the other hand this combined error is what a user has to deal with in practice. An extended discussion on the topic can be found in (Reinhart and Andersen 2006).

This paper uses the NRC daylighting test cases to evaluate the simulation capabilities of two simulation programs, 'Autodesk® 3ds Max® Design 2009' (3ds Max Design) and Daysim3.0 (Daysim). The two programs and simulation procedures used are described in section 2. Simulation results are compared to measurements in section 3 and discussed in section 4. Concluding remarks are presented in section 5.

2 Methodology

2.1 Daylighting Test Cases

As explained above, all test case measurements were collected in the East room of the NRC Daylighting Laboratory. The laboratory consists of two identical sidelit spaces which are facing South-southeast (25.2^{o} from due South). The East room is 2.85 m wide, 2.96 m high and 4.5 m deep and has a window-to-wall-area of 58% (Figure 2).



(a)

(b)

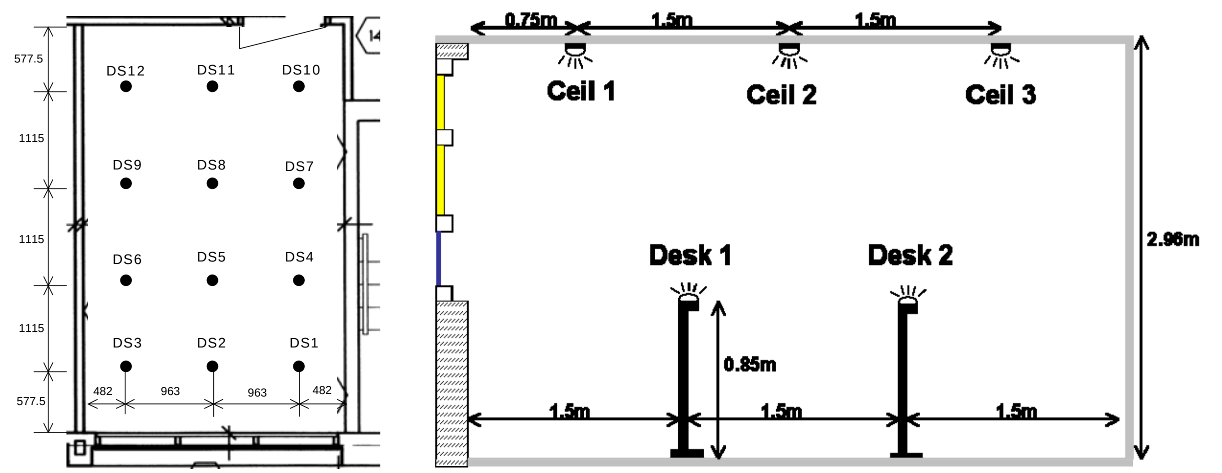
Figure 2: (a) Façade Section for TC1 Base Case; (b) internal view of the test room with the lightshelf.

[2] The full BRE data set also contains data measurements for spaces with more complex fenestration systems e.g. a mirrored lightshelf, mirrored louvres, and two prismatic glazings (Aizlewood 1993). To be of use today, the original samples would need to be available for optical measurement. Additionally, the precise positioning and orientation of the systems during the monitoring period would have to be known. More than a decade on, it is uncertain if all the necessary samples are available, or if the information on their deployment is sufficiently complete (private communication with John Mardaljevic).

Figure 2(b) shows that there is a roughly 1.9 m high hedge in close vicinity to the two test rooms. The hedge was planted to visually separate the test rooms form the building surroundings, giving somebody working in the test rooms an enhanced feeling of privacy. This measure was required since the test room is also used for human subject research. For the duration of the test case measurements, the hedge was covered with a black cloth to reduce simulation errors due to inaccurate reflectances of the hedge.

Interior illuminance measurements were taken with fifteen Licor illuminance sensors for TC1, TC2, TC4, and TC5 and five Licor illuminance sensors for TC3. All Licors were calibrated before and after the experiment and the measurement error of all sensors was determined to lie within a 5% band. Most outdoor direct and diffuse irradiances and illuminances were collected every 30 seconds using a Yankee rotating shadowband radiometer. For eight of the fourteen measurement days for test case TC1 a BF3 sensor was used to collect outside direct and diffuse irradiances as the Yankee had unexpectedly stopped running on these days. Both measurement devices are part of the NRC weather station which is located on the roof of NRC Building M24 in which the daylighting laboratory is housed.

For TC1, TC2, TC4 and TC5 interior illuminances were collected on a grid of twelve upward facing illuminance sensors at desk height (85cm above the ground) (Figure 3(a)). For TC3 only two work plane illuminances were collected on the central axis of the room at 1.5 m and 3.0 m distance from the façade (Figure 3(b)[3].



(a) (b)

Figure 3: (a) Floor plan of the test space: For test cases TC1, TC2, TC4, and TC5 twelve work plane sensors were arranged in a three by four sensor gird, dimensions are in mm; (b) Section of the test space: For test case TC3 only two work plane sensors were collected.

For all five test cases ceiling illuminances were collected at three locations along the central axis of the test space (Figure 4).

[3] The reason for this discrepancy is that the translucent panel data had previously been collected for a different validation study (Reinhart and Andersen 2006).

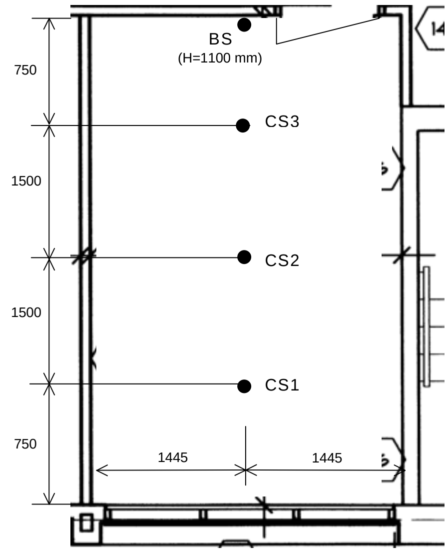


Figure 4: Inverted floor plan of the test space with the three ceiling illuminance sensors. Dimensions are in mm.

In order to model the space in various daylight simulation programs detailed SketchUp models of all five test cases were generated (SketchUp last accessed December 2008). The estimated tolerance for modeling errors in the geometry is below 20 mm. A visualization of the TC1 SketchUp model is shown in Figure 5. The East Room is the one on the right. Since previous simulation studies have shown that modeling the exterior ground is crucial, the hedge and the surrounding ground adjacent to the test space were geometrically modeled as well. In the SketchUp models each material is based on a different layer. Complementing the geometry files, the optical characteristics of all materials were carefully measured and documented in Table 1. All materials were set to gray using a relative weighing function of 30%, 59% and 11% for the RGB color channels. Table 1 also documents how all materials were modeled in Daysim (Radiance materials) and 3ds Max Design. Given that the list of parameters for the 3ds Max Design 'Arch & Design Material' is very long, only parameters that diverge from their default values are listed in Table 1. Towards the end of Table 1 is a list that links the parameters to their corresponding 3ds Max Design user interface entries. All colors are expressed on a scale of 0-255 in floating point precision.

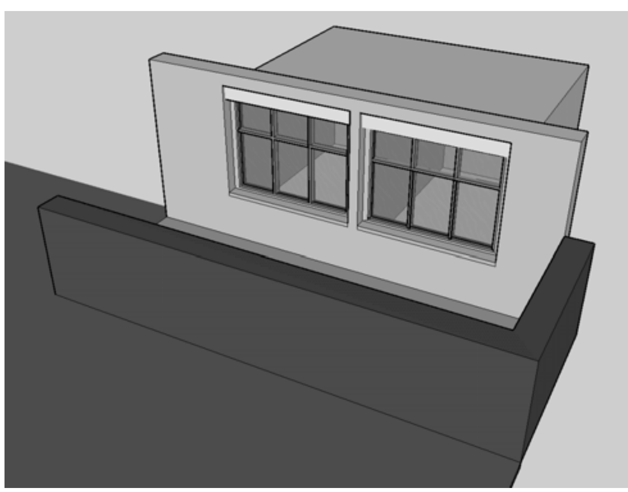


Figure 5: Visualization of the SketchUp model for TC1.

Table 1: Optical properties of all materials in the NRC Daylighting Laboratory.

Layer Name	Description	Measurement Description	Material modifier in Daysim/Radiance	Arch & Design Material Parameters in 3ds Max Design *
InteriorBackWall	Back wall	Three Minolta CM2500d spectrophotometer measurements of different wall sections. Results**:** 77% diffuse reflectance, 0.4% specular reflectance.	void plastic InteriorBackWall 0 0 5 0.77 0.77 0.77 0.004 0	#diff_color (color 197 197 197) #refl_weight 0.004 #refl_func_low 1.0 #refl_func_high 1.0
InteriorCeiling	Ceiling	Six Minolta CM2500d spectrophotometer measurements of different parts of the ceiling. Results: 88% diffuse reflectance, 0.1% specular reflectance.	void plastic InteriorCeiling 0 0 5 0.88 0.88 0.88 0.001 0	#diff_color (color 224.765 224.765 224.765) #refl_weight 0.001 #refl_func_low 1.0 #refl_func_high 1.0
InteriorFloor	Carpet	Nine Minolta CM2500d spectrophotometer measurements of dark, light and pale areas on the carpet. Results: 12% mean diffuse reflectance, no specular reflectance.	void plastic InteriorFloor 0 0 5 0.12 0.12 0.12 0 0	#diff_color (color 30.49 30.49 30.49) #refl_weight 0.0
InteriorFrontWall	Inside of exterior wall (façade)	Three Minolta CM2500d spectrophotometer measurements of different wall parts. Results: 75% diffuse reflectance, 0.6% specular reflectance.	void plastic InteriorFrontWall 0 0 5 0.75 0.75 0.75 0.006 0	#diff_color (color 192.255 192.255 192.255) #refl_weight 0.006 #refl_func_low 1.0 #refl_func_high 1.0
InteriorSideWall	Side walls	Different for TC3 and other test cases. **TC.3:** Same as back wall. **Other test cases:** Six Minolta CM2500d spectrophotometer measurements of different wall parts. Results: 38% diffuse reflectance, 0.4% specular reflectance	**TC.3:** void plastic InteriorSideWall 0 0 5 0.77 0.77 0.77 0.004 0 **Other test cases:** void plastic InteriorSideWall 0 0 5 0.38 0.38 0.38 0.004 0	**TC.3:** #diff_color (color 186.15 186.15 186.15) #refl_weight 0.0 **Other test cases:** #diff_color (color 192.255 192.255 192.255) #refl_weight 0.004 #refl_func_low 1.0 #refl_func_high 1.0
MoullionMetalSilver	Mullions (unpainted aluminum)	Six Minolta CM2500d spectrophotometer measurements of different mullion parts (inside and outside). Results; 62% diffuse reflectance, 7% specular reflectance	void plastic MoullionMetalSilver 0 0 5 0.62 0.62 0.62 0.07 0	#diff_color (color 170.745 170.745 170.745) #refl_weight 0.004 #refl_func_low 1.0 #refl_func_high 1.0
ExteriorParkingLot	Surface of exterior parking lot	Five Minolta CM2500d spectrophotometer measurements of different parts of the parking	void plastic ExteriorParkingLot 0 0	#diff_color (color 28 28 28) #refl_weight 0.0

Layer Name	Description	Measurement Description	Material modifier in Daysim/Radiance	Arch 7 Design Material Parameters in 3ds Max Design
		lot. Results: 11% diffuse reflectance, no specular reflectance	5 0.11 0.11 0.11 0 0	
ExteriorGravelNearFacade	Exterior ground between façade and hedge	Different for TC3 and other test cases. For TC.3 the gravel was exposed whereas it was covered with black cloth for the other test cases. **TC.3:** 22% diffuse reflectance. **Other test cases:** 0% diffuse and specular reflectance (approximated value)	**TC.3:** void plastic ExteriorGravelNearFacade 0 0 5 0.22 0.22 0.22 0 0 **Other test cases:** void plastic ExteriorGravelNearFacade 0 0 5 0 0 0 0 0	**TC.3:** #diff_color (color 51 51 51) #refl_weight 0.0 **Other test cases:** #diff_color (color 0 0 0) #refl_weight 0.006
ExteriorWall	Exterior wall	Three Minolta CM2500d spectrophotometer measurements of different wall parts. Results: 58% diffuse reflectance, 0.1% specular reflectance	void plastic ExteriorWall 0 0 5 0.58 0.58 0.58 0 0	#diff_color (color 192.255 192.255 192.255) #refl_weight 0.006 #refl_func_low 1.0 #refl_func_high 1.0
ExteriorBlackCloth	Black cloth covering the hedge	0% diffuse and specular reflectance (approximated value)	void plastic ExteriorBlackCloth 0 0 5 0 0 0 0 0	#diff_color (color 0 0 0) #refl_weight 0.006
DoubleClearGalzing	Clear double glazing	Clear double glazing with a direct normal visual transmittance of 66.1%. This corresponds to a transmissivity of 72.0%. Measurement: With lamp QI105, at 6.5A (or 260.032mV across R) and LiCor LI250 with Photometric sensor LI210SA Ph5520, lined up on the rail perpendicular to the light path. Took a measurement with Licor: 1065.7 Lux Moved the window in the light path, flush against the light box (so perpendicular to the light path) and took another measurement: 703.9 Lux.	void glass DoubleClearGalzing 0 0 3 0.72 0.72 0.72	#diff_color (color 0 0 0) #refl_color (color 255 255 255) #refl_gloss 1.0 #refl_weight 1.0 #refr_color (color 207 207 207) #refr_gloss 1.0 #refr_ior 1.5 #refr_weight 1.0 #refl_func_fresnel false #refl_func_low 0.0 #refl_func_high 1.0 #refl_func_curve 4.816 #opts_1sided true #opts_do_refractive_caustics false #opts_skip_inside true #opts_backface_cull false

Layer Name	Description	Measurement Description	Material modifier in Daysim/Radiance	Arch 7 Design Material Parameters in 3ds Max Design
Lightshelf	Light shelf	Three Minolta CM2500d spectrophotometer measurements of different parts of the light shelf. Results: 83% diffuse reflectance, 0.2% specular reflectance	void plastic Lightshelf 0 0 5 0.83 0.83 0.83 0.002 0	#diff_color (color 212.255 212.255 212.255) #refl_weight 0.002 #refl_func_low 1.0 #refl_func_high 1.0
ExternalWindowSill	External window sill	Six Minolta CM2500d spectrophotometer measurements of different mullion parts. Results: 60% diffuse reflectance, 15% specular reflectance	void plastic ExternalWindowSill 0 0 5 0.60 0.60 0.60 0.15 0	#diff_color (color 178.49 178.49 178.49) #refl_weight 0.15 #refl_func_low 1.0 #refl_func_high 1.0
InternalVenetianBlinds	Internal venetian blinds	Four Minolta CM2500d spectrophotometer measurements of different parts of the venetian slats (top and bottom). Results:74% diffuse reflectance, 2% specular reflectance	void plastic InternalVenetianBlinds 0 0 5 0.74 0.74 0.74 0.02 0	#diff_color (color 192.49 192.49 192.49) #refl_weight 0.02 #refl_func_low 1.0 #refl_func_high 1.0
ExternalVenetianBlinds	External venetian blinds	Four Minolta CM2500d spectrophotometer measurements of different parts of the venetian slats (top and bottom). Results:41% diffuse reflectance, 6% specular reflectance	void plastic ExternalVenetianBlinds 0 0 5 0.41 0.41 0.41 0.06 0	#diff_color (color 111.255 111.255 111.255) refl_weight 0.06 #refl_func_low 1.0 #refl_func_high 1.0
ExternalVenetianBlindsBox	External venetian blinds box	Same material as external venetian blinds slats.	void plastic ExternalVenetianBlindsBox 0 0 5 0.41 0.41 0.41 0.06 0	#diff_color (color 111.255 111.255 111.255) refl_weight 0.06 #refl_func_low 1.0 #refl_func_high 1.0
TranslucentMullion	White mullion for the translucent panel	Based on comparing luminance of the mullion with luminances coming of a reference sample. Results: 74% diffuse reflectance, no specular reflectance	void plastic TranslucentMullion 0 0 5 0.74 0.74 0.74 0 0	#diff_color (color 191.25 191.25 191.25) #refl_weight 0.1 #refl_func_low 1.0 #refl_func_high 1.0
TranslucentBlackStripes	Translucent black stripes	0% diffuse and specular reflectance (approximated value)	void plastic TranslucentBlackStripes 0 0 5 0 0 0 0 0	#diff_color (0 0 0) #refl_weight 0.0

TranslucentPanel	Translucent panel	Based on goniophotometer and integrating sphere measurements (Reinhart and Andersen 2006). Result: Translucent panel with a direct diffuse-diffuse transmittance of 16%'	void transdata TranslucentPanel 4 noop refl.dat rang.cal rang 0 6 0.40446 0.40446 0.40446 0.08 0.435635 1	#diff_weight 0.0 #refr_color (color 255 255 255) #refr_trans_on true #refr_transc (color 41.3355 41.3355 41.3355) #refr_transw 1.0 #opts_1sided true
TranslucentCentralGlazing	Translucent central glazing	Based on integrating sphere measurements (Reinhart and Andersen 2006). Result: Tinted double glazing with a direct normal visible transmittance of 31%. This corresponds to a transmissivity of 34%.	void glass TranslucentCentralGlazing 0 0 3 0.34 0.34 0.34	#diff_color (color 0 0 0) #refl_color (color 255 255 255) #refl_gloss 1.0 #refl_weight 1.0 #refr_color (color 148.691 148.691 148.691) #refr_gloss 1.0 #refr_ior 1.5 #refr_weight 1.0 #refl_func_fresnel false #refl_func_low 0.0 #refl_func_high 1.0 #refl_func_curve 4.816 #opts_1sided true #opts_do_refractive_caustics false #opts_skip_inside true #opts_backface_cull false

*) The variables correspond to the following 3ds Max Design User Interface entries:

#diff_color	Diffuse Color
#refl_weight	Reflection | Reflectivity Amount
#refl_gloss	Reflection | Glossiness
#refr_weight	Reflection | Transparency Amount
#refr_color	Refraction | Transparency Color
#refr_gloss	Refraction | Glossiness
#refr_ior 1.5	Refraction | IOR
#refl_func_fresne	BRDF | Custom Reflectivity Function
#refl_func_low	BRDF | 0 deg Reflectivity
#refl_func_high	BRDF | 90 deg Reflectivity
#refl_func_curve	BRDF | Curve Shape
#opts_1sided true	Advanced Transparency Options | Thin-Walled
#opts_do_refractive_caustics	Advanced Transparency Options | Use Transparent Shadows
#opts_skip_inside	Advanced Transparency Options | Skip Reflections on Inside
#opts_backface_cull	Advanced Transparency Options | Back Face Culling

For all test cases measurements were taken under a variety of sunny and cloudy sky conditions (Table 2). While the original measurement interval was 30 seconds the data was averaged down to 15 minute time step intervals. Table 2 reports the number of sky conditions collected for each test case when the outside vertical façade illuminance was over 1000 lux.

Table 2: Overview of the number of sky conditions (15 minute averages) that were considered for each test case.

	# of sunny skies *	# of cloudy skies	total # of sky conditions
TC 1 No Shading	1678	636	2314
TC 2 Lightshelf	1488	779	2267
TC 3 Translucent Panel	1991	1116	3107
TC 4 External Venetian Blinds	1113	910	2023
TC 5 Internal Venetian Blinds	1311	440	1751

*) A sky was defined to be 'sunny' if the direct normal solar radiation is above $50Wm^{-2}$.

2.2 Daysim Simulations

Daysim is a Radiance-based advanced daylighting analysis tools that uses a daylight coefficient approach combined with the Perez all weather sky model (Perez, Seals and Michalsky 1993) to predict hourly or sub-hourly time series of interior daylighting conditions based on direct and diffuse irradiances taken from a TMY file. Since Radiance in its original form ('Radiance Classic') simulates lighting conditions due to daylight under one sky condition at a time and since each calculation typically takes several minutes to hours, Daysim was developed to more efficiently calculate illuminance or luminance time series under varying sky conditions (Reinhart and Walkenhorst 2001). A Daysim analysis typically extends over a whole calendar year and includes thousands of sky conditions. In order to process that many sky conditions within a reasonable time frame Daysim uses a daylight coefficient approach: Daylight coefficients are a mathematical construct that describes how much a certain part of the sky (sky patch) contributes to the daylight at a sensor point within a building (P R Tregenza 1983). Once a complete set of daylight coefficients has been calculated for each sensor point of interest the daylight coefficients can be combined with any sky condition in order to determine the amount of daylight at the sensor point under that particular sky condition.

Daysim results tend to be very similar to Radiance Classic results especially under overcast sky conditions. Under sunny sky conditions Daysim simulation results can somewhat diverge from Radiance since Daysim interpolates direct solar contributions for particular sky conditions from four neighboring, representative sky conditions. Daysim3.0 uses the recently developed DDS (dynamic daylight simulation) daylight coefficient file format combined with direct shadow testing at each time step to get as close to Radiance Classic as possible (Bourgeois, Reinhart and Ward 2008). Note though that the Daysim results reported in this study are not identical to those Radiance Classic would have generated.

In order to model the five test cases in Daysim a publicly available SketchUp plug-in, developed by Thomas Bleicher, was used that exports SketchUp scenes into Radiance format (Bleicher (last accessed in December 2008)). All materials were modeled according to Table 1. Table 3 lists the simulation parameters that were used for all five test cases. These simulation parameters were chosen based on recommended values from earlier Daysim validation studies and correspond to a scene of 'high complexity' as defined in the Daysim tutorial (Reinhart 2006).

Table 3: Utilized Radiance simulation parameters.

ambient bounces	ambient division	ambient sampling	ambient accuracy	ambient resolution	direct threshold
7	1500	100	0.05	300	0

2.3 3ds Max Design Simulations

Lighting calculations using 3ds Max Design are based on Exposure™ technology. Exposure™ is a lighting analysis feature that includes a 'shader' of the Perez Sky Model. In other words when using the same input parameters 3ds Max Design uses the same sky luminance distribution as Daysim.

For the global illumination calculation Exposure™ uses the mental ray® raytracer. Global illumination is the simulation of all light inter-reflection effects in a scene. mental ray® offers two fundamental approaches to compute global illumination which can be used together: Forward raytracing (photon mapping) and backward raytracing (final gathering) (mental-images 2007). mental ray® uses a kd-tree algorithm to speed up the ray intersection. It supports a variety of lighting phenomena including reflections, refractions, global illumination, and subsurface scattering. Similar to the ambient interpolation feature in Radiance full final gather tracing in mental ray® is performed only on distinct and well-selected surface points (sensors). All other surface points interpolate the global illumination contribution from nearby final gather points. Discrete 3ds Max Design simulations were run for each measured sky condition individually. For each test case the required simulation time to calculate indoor illuminances under a single sky condition was in the order of 6 to 12 seconds on a 2 Quad Core Xeon Processor (2.66Ghz). A discussion of the required simulation times for 3ds max Design and Daysim is presented in section 4.3.

Table 4 lists the mental ray® simulation settings in 3ds Max Design that were used in this study. Since this is the first experimental validation study of 3ds Max Design, the simulation parameters were initially optimized based on the measurements from the five test cases. The optimization process included both simulation accuracy as well as simulation time. Once a set of simulation parameters had been selected, they were consistently used for all five test cases. Parameters that are not listed in Table 4 were left at their default values. The optimization procedure concluded that the most relevant parameters to increase or decrease accuracy of indirect illumination calculations were found to be the number of rays per FG Point and the number of Diffuse Bounces. These parameters resemble the ambient bounce and ambient division parameters in Radiance. A sensitivity analysis revealed that beyond 2000 rays per sample, the simulation reached an acceptable level of accuracy while still providing simulation results within a reasonable time frame.

Light sensors in 3ds Max Design were specified using the Light Meter helper object. It is important to note that Light Meter objects actually cast eight times (8x) more rays than what has been set in the Render Setup Dialog of 3ds Max Design.

Table 4: Utilized 3ds Max Design simulation parameters.

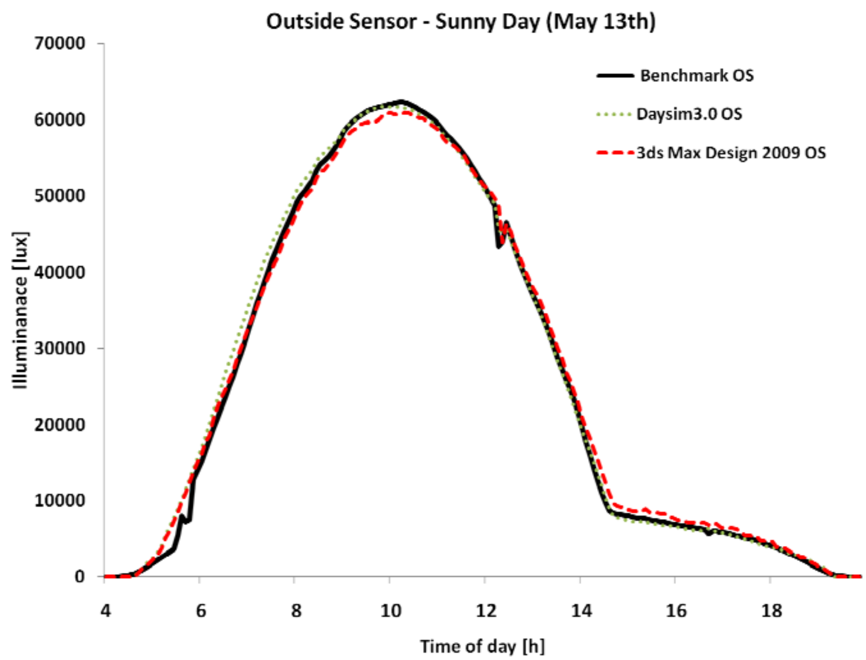
3ds Max Render Dialog Rollout	Section	Parameter
Rendering Algorithms	Scanline	Enable: Off
Rendering Algorithms	Raytracing	Enable: On Max Trace Depth: 10 Max Trace Reflections: 10 Max Trace Refractions: 10
Shadows & Displacement	Shadows	Enable: On Mode: Simple
Final Gather	Basic	Enable Final Gather: On Multiplier: 1.0 Initial FG Point Density: 1.0 Rays per FG Point: 2500 Interpolate Over Num. FG Points: 5 Diffuse Bounces: 6 Weight: 1.0
Final Gather	Advanced	Noise Filtering: None Max Depth: 10 Max Reflections: 10 Max Refractions: 10 Use Falloff (Limit Ray Distance): Off
Final Gather	FG Point Interpolation	Use Radius Interpolation Method: Off
Caustics & Global Illumination (GI)	Caustics	Enable: Off
	Global Illumination	Enable: Off

3 Results

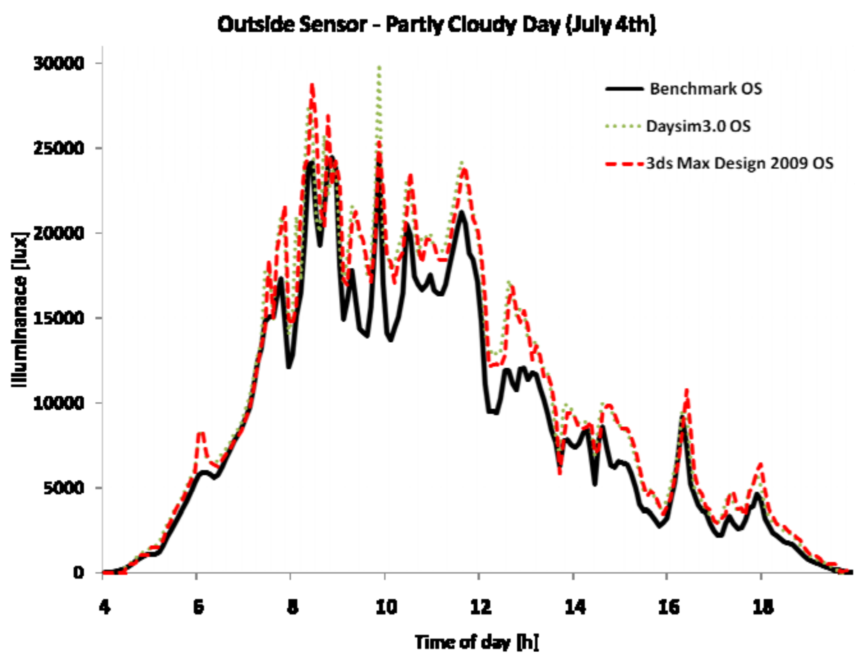
In this section simualtion results from 3ds Max Design and Daysim are compared to measured indoor and outdoor illuminances.

3.1 Façade Illuminances

Figure 5 compares simulation results for 3ds Max Design and Daysim to measurements for the outside vertical facade sensor that is facing South-southeast (25.2 Deg East of South) on a sunny (a) and a partly cloudy (b) day. In this and later figures the measured data is indicated by the line labeled “Benchmark”. The figure shows that both simulation programs predict close to identical outside façade illuminances under sunny and cloudy sky conditions. One would expect this finding as both programs are based on the same sky model. Under sunny sky conditions the simulations are within a 5 to 10% error band with respect to measurements showing that direct solar contributions are correctly modeled by both programs. Under partly cloudy sky conditions the simulations closely follow the up and down movements of the measurements and mostly lie within a 10 to 15% error band but - at times - simulations diverge by as much as 37% from the measurements. These findings reproduce those from earlier validation studies and show that the Perez model reaches its limits under partly cloudy sky conditions with quickly varying cloud cover (Reinhart and Walkenhorst 2001).



(a)



(b)

Figure 5: Measured and simulated vertical façade illuminances on the outside sensor on (a) a sunny and (b) a partly cloudy day.

3.2 Base Case (TC1) and Lightshelf (TC2)

Figure 6 shows measured and simulated indoor illuminances for an upward facing desktop sensor near the façade (DS2 in Figure 3(a)) for the sunny day from Figure 5(a) for the base case (TC1). The pronounced variations in Figure 6(a) from over 40000 lux to below 7000 lux at about 9.45 AM and 10.45 AM were caused by the two vertical window mullions shading the sensor. Both simulation programs successfully model the effect. Note though that Daysim and the measurements only show a fifteen-minute peak at around noon whereas the 3ds Max Design peak is a bit wider. These differences are likely caused by slight difference of where 3ds Max Design and Daysim predict the sun to be located on the celestial hemisphere. Such differences can occur when a sensor is exposed to or shaded from direct sunlight for a brief time interval.

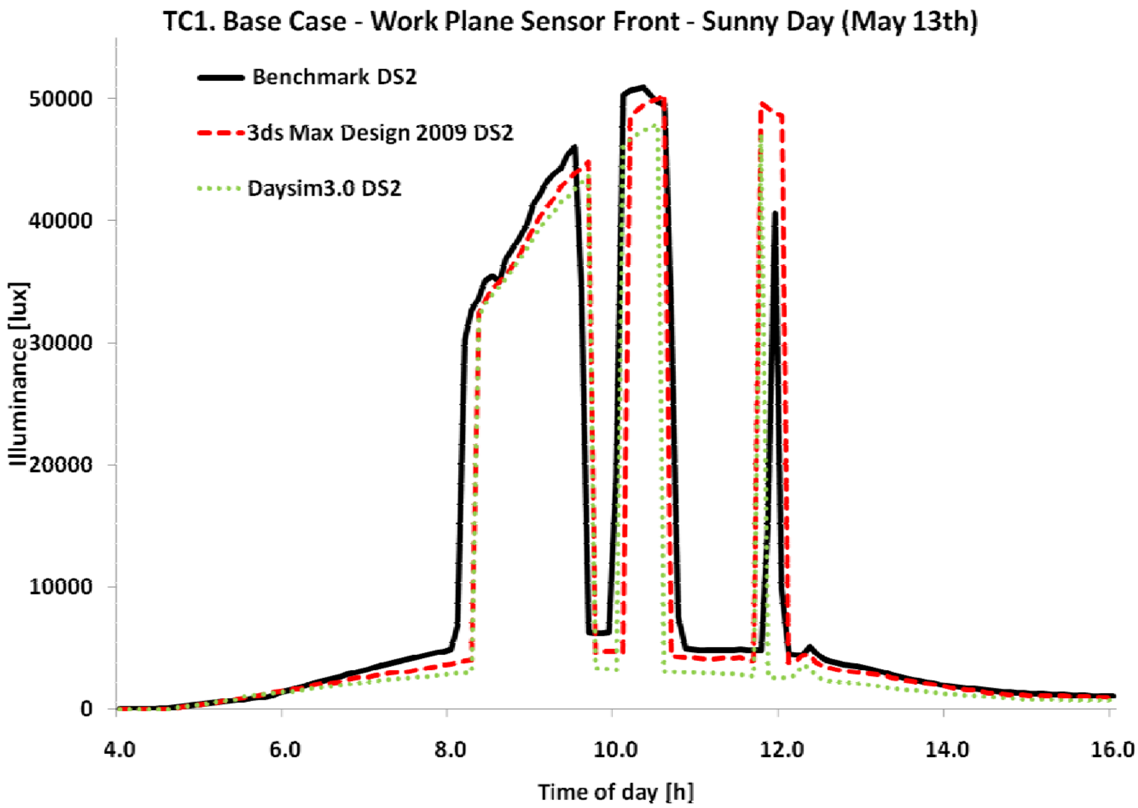
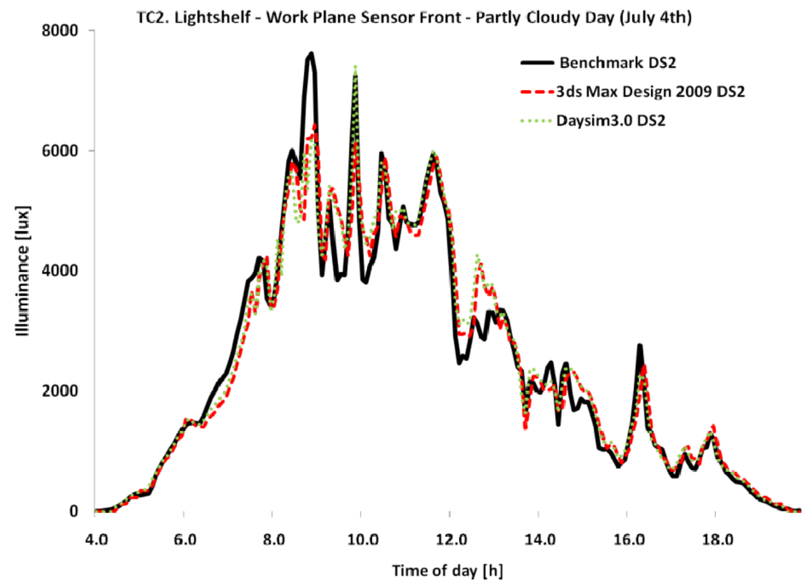
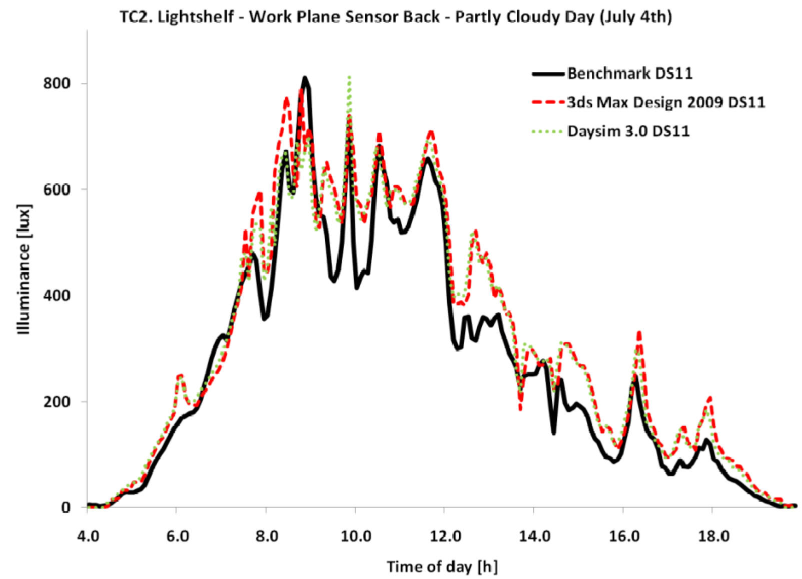


Figure 6: Measured and simulated illuminances for an upward facing work plane sensor close to the façade for TC1 (base case).

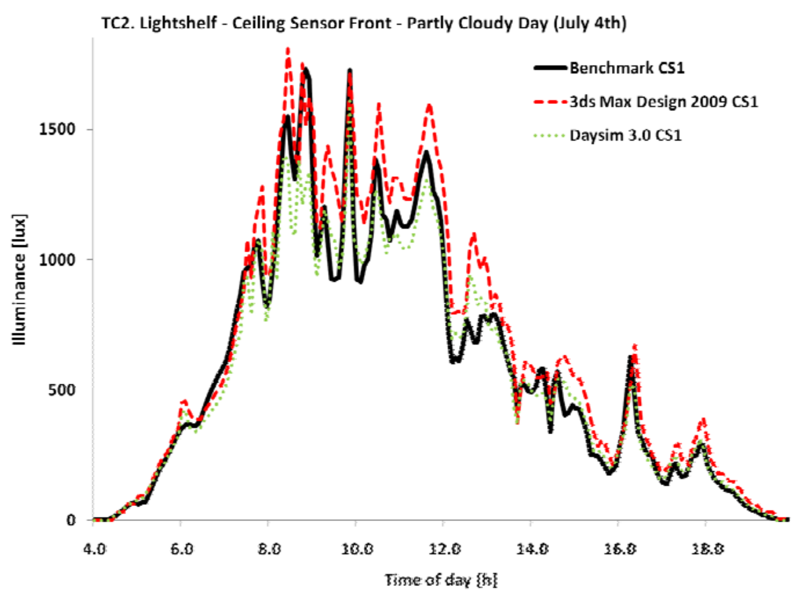
Figure 7 compares measured and simulated illuminances for various sensors for the lightshelf case (TC2) on the partly cloudy day from Figure 5(b). The figure shows that 3ds Max Design and Daysim simulations are very close under partly cloudy sky conditions and reproduce well the measurements for a variety of locations within the space. Note that the range of illuminances for the different sensors varies from under 100 lux to over 6000 lux covering the whole spectrum of illuminance conditions that are typically encountered in buildings.



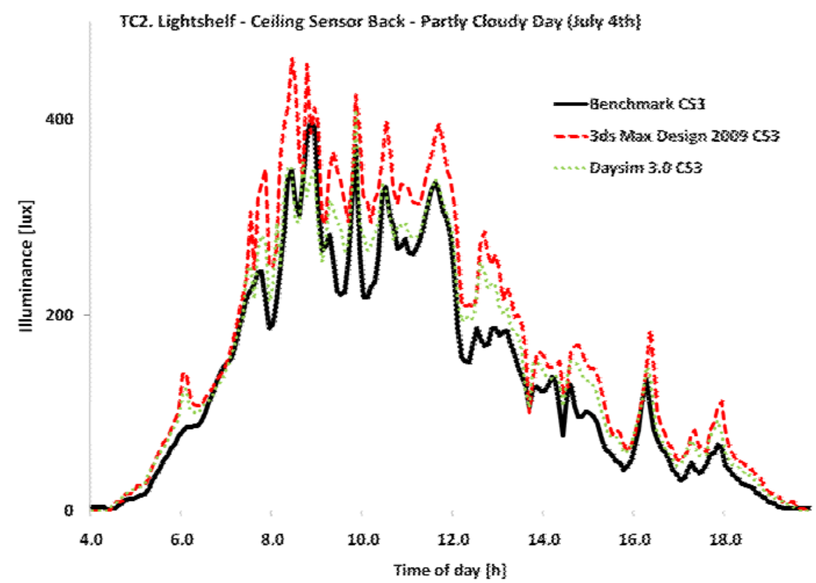
(a) Work plane sensor front



(b) Work plane sensor back



(c) Ceiling sensor front



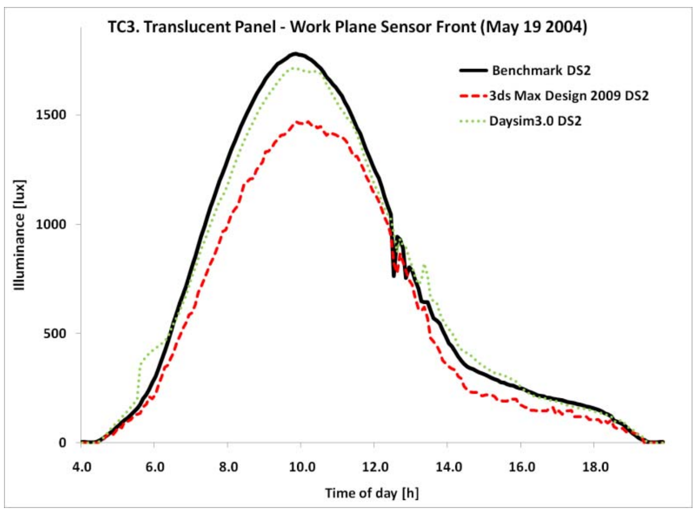
(d) Ceiling sensor back

Figure 7: Measured and simulated illuminances for several indoor sensors for TC2 Lightshelf on a partly cloudy day.

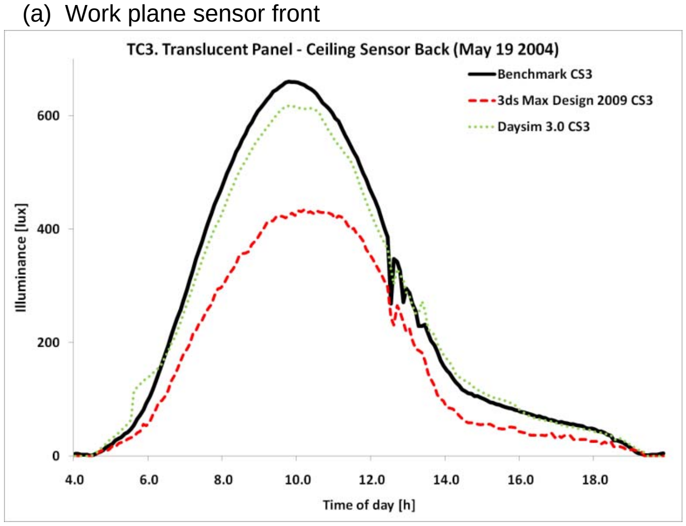
3.3 Translucent Glazing (TC3)

TC3 explores how the two simulation programs manage to simulate a 'non standard' material such a translucent panel. The panel was previously characterized using goniophotometer and integrating sphere measurements (Reinhart and Andersen 2006). As shown in Table 1, Daysim results are based on a transdata material modifier that models the angle dependant direct hemispherical transmittance of the panel according to integrating sphere measurements. In 3ds Max Design the panel was modeled as an ideal diffuser. According to the integrating sphere measurements the diffuse-diffuse hemispherical transmittance of the diffuser was set to 16% (Reinhart and Andersen 2006).

Figure 8 shows simulated and measured indoor illuminances under a sunny day for a front work plane sensor and a back ceiling sensor. As shown before (Reinhart and Andersen 2006), Daysim closely follows the measurements. 3ds Max Design reproduces the overall behavior of the measurements but there is a constant 'offset' between measurements and simulations suggesting that the diffuse transmittance specified for the translucent panel in mental ray® is lower than the input value of 16%. According to the Autodesk Media and Entertainment Division 'Autodesk is working with mental images [the makers of mental ray®] to resolve this issue'[4].



(a) Work plane sensor front



(b) Ceiling sensor back

Figure 8: Measured and simulated illuminances forTC3 Translucent Panel.

[4] Private communication with Autodesk 3ds Max Design development team (January 2008).

3.4 Venetian Blinds (TC4 and TC5)

Test cases TC4 and TC5 evaluate how well a simulation program can model a complex fenestration system (CFS) such as external (TC4) or internal (TC5), downward-curved, venetian blinds. For both test cases the blinds were fully lowered. The external venetian blind system was a *split blind* system meaning that the upper third of the slats can be adjusted to be more open than the lower slats (Figure 9(a)). The external blinds were controlled by an electric motor that synchronously readjusted the height of the blinds (occlusion) as well as the slat angle. The internal blinds (TC5) were a standard, manually adjusted system. For both systems the slats were set as close to horizontal as possible. That proved to be somewhat of a challenge for the motorized blinds. Due to the ratio of the slat depth to the vertical distance between two slats, most incoming direct sunlight was reflected at least once off a slat before further penetrating into the room making the systems challenging to model. Another modeling challenge for these test cases was that the curved blind slats had some specular component which was estimated to be 6% for the external venetian blinds and 2% for the internal venetian blinds using a Minolta CM2500d spectrophotometer (see Table 1). The curvature of the blinds was measured as accurately as possible for both venetian blind systems. Despite the importance of the blinds' curvature for the simulation results it is one of the simulation inputs that are most prone to errors due to measurement uncertainties and differences between individual slats.

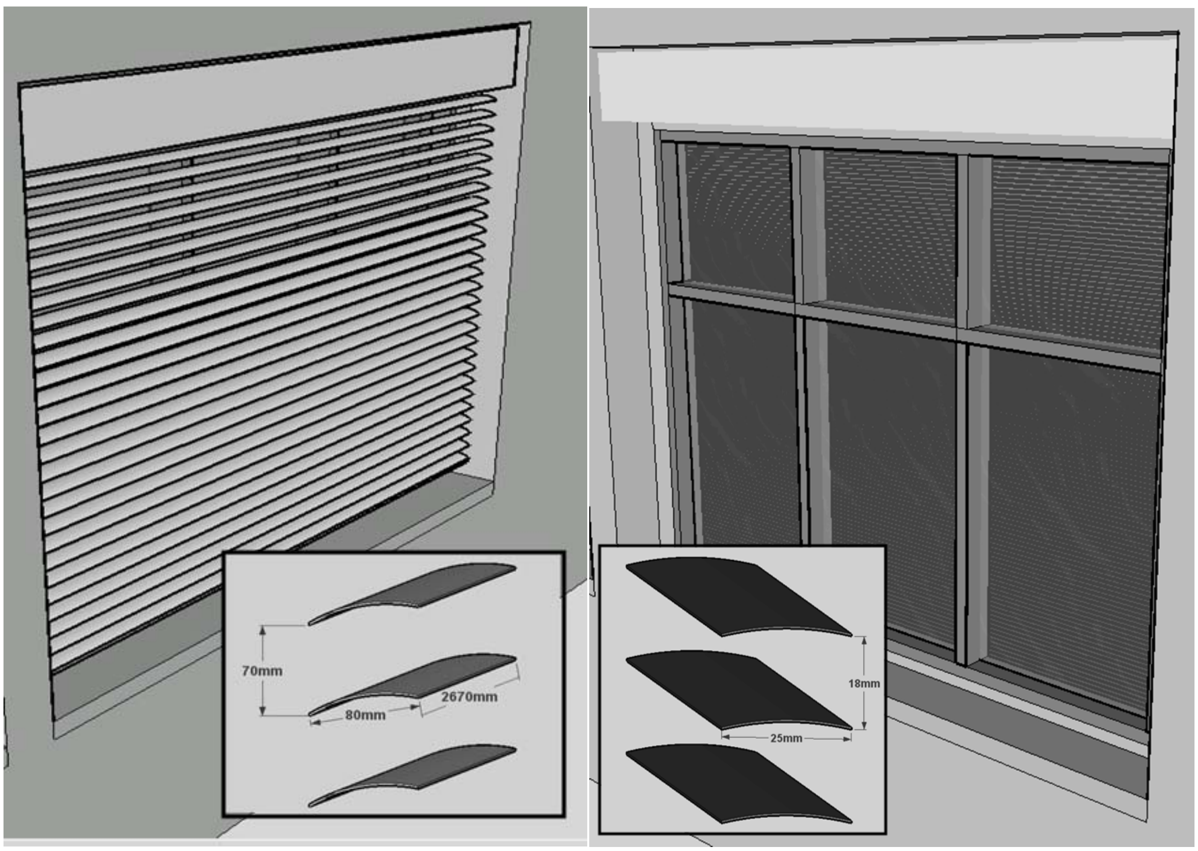
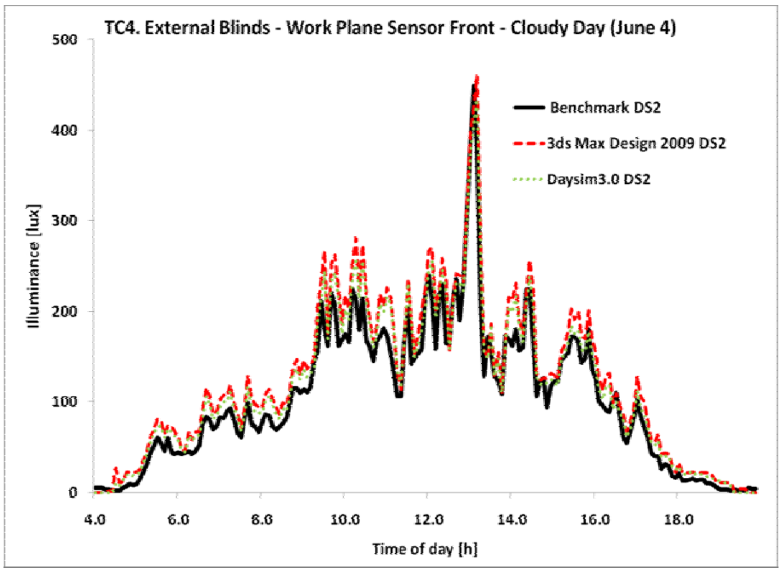


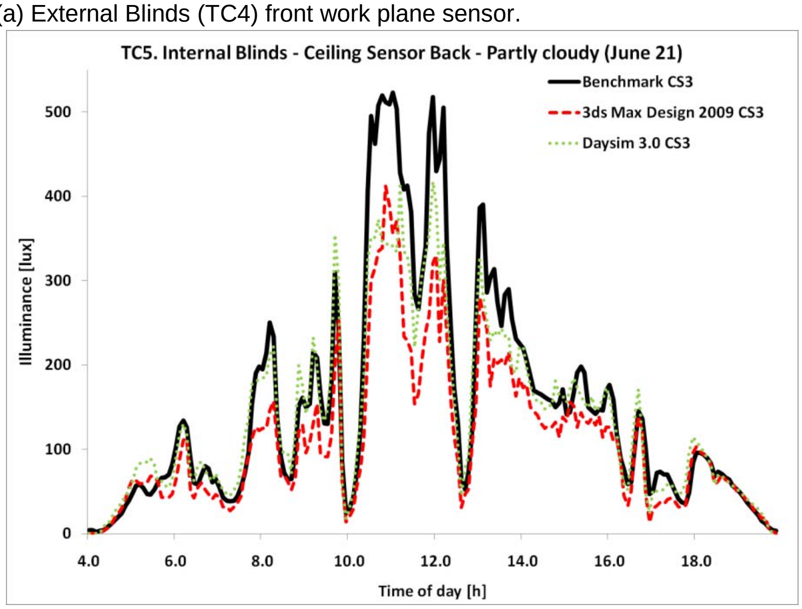
Figure 9: Visualizations of the external (a) and internal (b) venetian blinds used in test cases TC4 and TC5, respectively.

Figure 10 shows simulated and measured illuminances under cloudy and partly cloudy sky conditions for a front row work plane sensor for TC4 and a back ceiling sensor for TC5. Despite the aforementioned complexity involved in modeling venetian blinds, both simulations closely reproduce the measured data at least under cloudy sky conditions. For the TC5 day (Figure 10(b)) the sky was temporarily partly cloudy to sunny from 10 AM to noon.

Figure 11 shows simulation results for the external venetian blinds (TC4) under clear sky conditions. Due to the setting of the blinds and the high position of the sun in the sky on June 10 in Ottawa at around 10 AM (around 55°) most incoming direct sunlight was reflected of one of the slats and therefore entering the space at an upward angle. The front ceiling sensor (Figure 11(a)) accordingly gives a good indication of how well the light redirecting effect of the blinds was modeled on that day. 3ds Max Design overestimates the amount of sunlight being reflected off the slats for most of the day whereas Daysim results are closer to the measurements except when the sun is roughly perpendicular to the façade (10 to 11 AM). The differences between the measurements and simulations are greatly reduced for both programs as the sun moves around the façade confirming that these simulation errors are caused by the programs' inability to correctly reproduce the sunlight's reflection off the blinds. These modeling uncertainties are not really surprising since (a) specular components of curved surfaces are hard to measure with a handheld spectrometer (ideally one would take goniophotometer measurements of a flat sample of the slat material) and (b) actual blind slat angles are hard to measure and somewhat vary from one slat to the next.



(a) External Blinds (TC4) front work plane sensor.

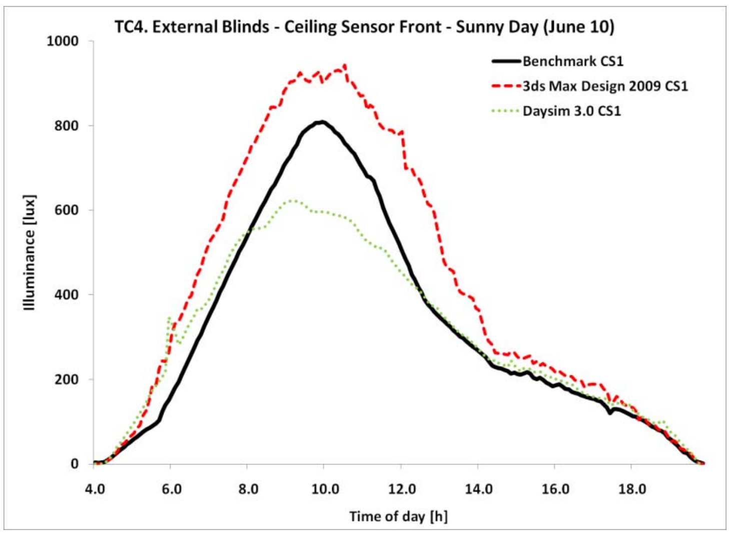


(b) Internal Blinds (TC5) back ceiling sensor

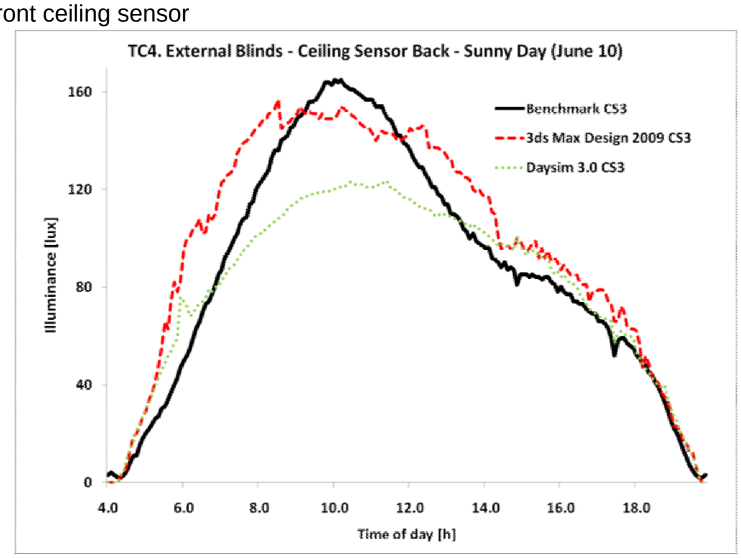
Figure 10: Measured and simulated illuminances for TC4 and TC5 under cloudy and partly cloudy sky conditions.

Given that the direct sunlight reflection is not fully represented by 3dsMax Design it is probably happenstance that the results are closer to the measurements for the back ceiling sensor (Figure 11(b)). Despite of the aforementioned experimental difficulties that one faces measuring the exact optical behavior of venetian blinds it is worthwhile pointing out that all measurements and simulations diverge by less than 40 lux for the back ceiling sensor while the outside illuminance onto the facade is over 50,000 lux. This shows that both simulation programs *in essence* capture the lighting conditions within the space.

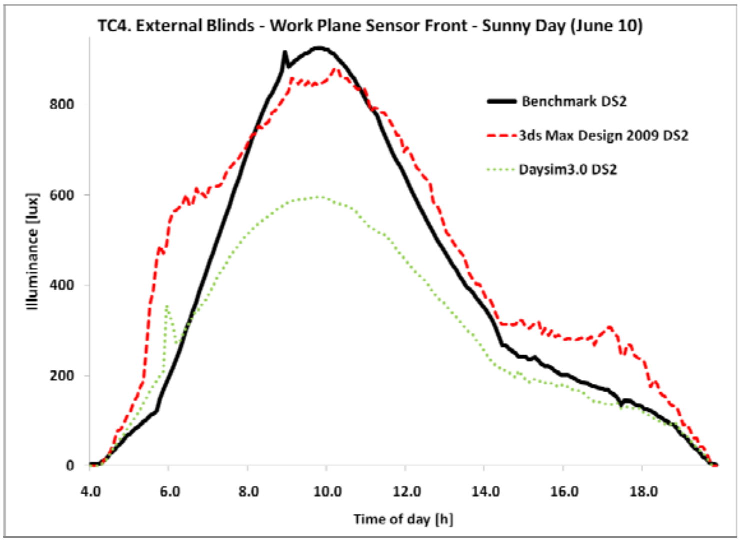
Figure 11(c) shows the results for the front work plane sensor. The 3ds Max Design results reproduce the peak illuminance for the sensor on that day very closely whereas Daysim results lie roughly 30% under the measured peak. The higher measured work plane illuminances relative to the simulations, compared to the results for the front ceiling illuminances, are very likely caused by light 'spilling' through between the side of the blinds and the window frame as well as through the cable holes in the slats, which were not modeled.



(a) Front ceiling sensor



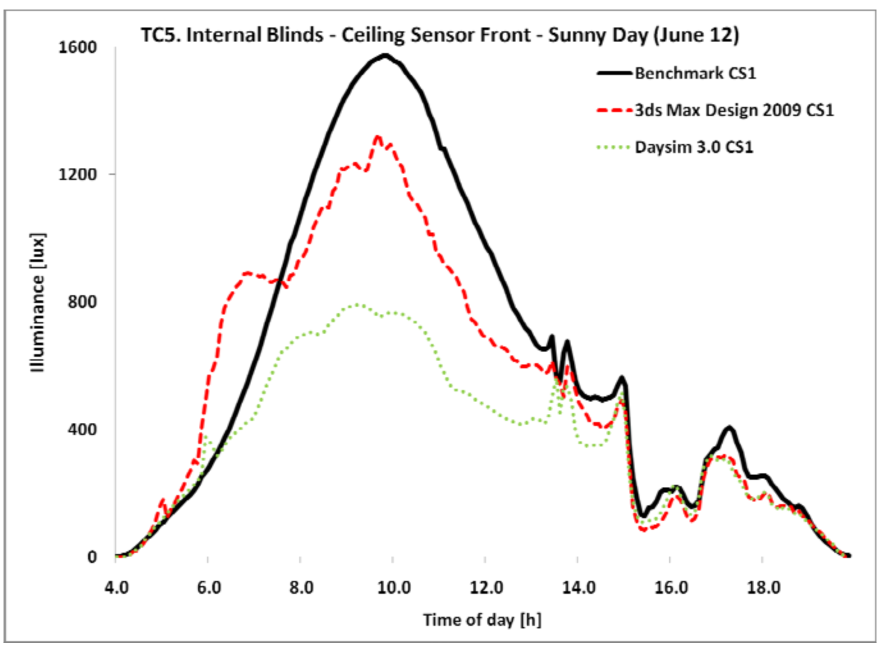
(b) Ceiling sensor back



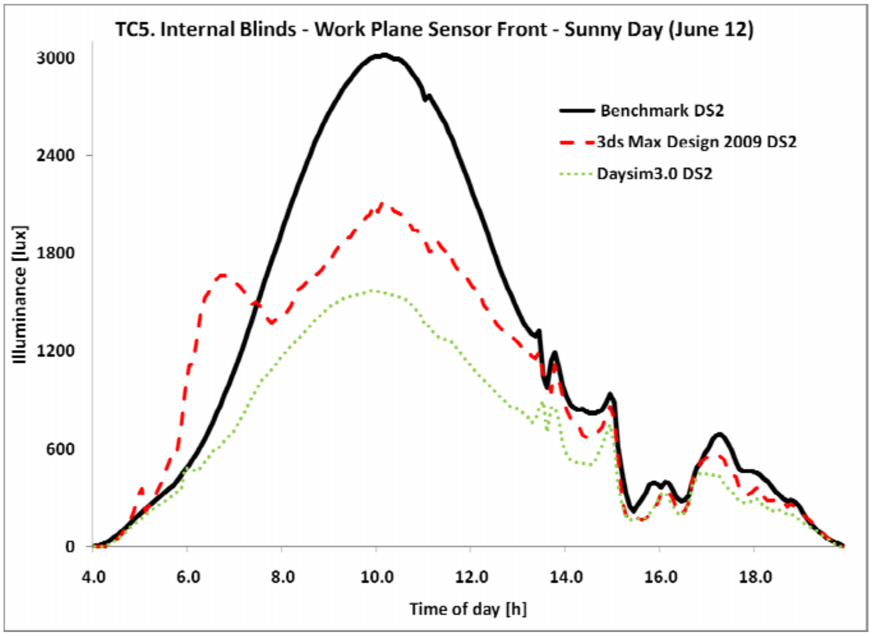
(c) Work plane sensor front

Figure 11: Measured and simulated illuminances for TC4 under sunny sky conditions.

Figure 12 shows the same results as Figure 11 for the internal venetian blinds (TC5). For this case both programs underestimate the light flux entering the space even though 3ds Max Design is a lot closer to the measured data (Figure 12(a)). For 3ds Max Design the relative difference between the measured and the simulated peaks for the work plane sensor (Figure 12(b)) is larger than for the front ceiling sensor, probably due to light spilling though and around the blind slats. It is unclear what caused the odd 'hump' in the 3ds Max Design simulations at around 6 AM that is visible for both indoor sensors but not for the outside facade sensor.



(a) Front ceiling sensor



(b) Work plane sensor front

Figure 12: Measured and simulated illuminances for TC5 under sunny sky conditions.

3.5 Error Analysis

In order to provide a more holistic analysis of the differences between the simulation programs compared to the measurements, the relative mean bias error (MBE) and the relative root mean square error (RMSE) with respect to the measurements were calculated for all five test cases (Table 5). The MBE and RMSE are statistical quantities to characterize the similarity/differences between two data series[5]. The relative MBE indicates the tendency of one data series to be larger or smaller than the other. The RMSE indicates how far one data series "fluctuates" around the other. As in earlier simulation studies measurements were only considered for the error analysis if the measured outside façade illuminance was above 5000 lux. This selection criterion was used since the Perez sky model (or any other comparable sky model) becomes sensitive to measurement uncertainties of input direct irradiances just after sunrise or before sunset. This can translate into very large relative simulation errors at times which are not really significant for an annual daylight simulation since interior illuminances are low. The 5000 lux filtering procedure reduced the number of sky conditions for all test cases to between 1401 and 2430. For test cases TC1, TC2, TC4 and TC5 errors for front and back work plane sensors are the mean of the three front row sensors (DS1, DS2 and DS3) and three back row sensors (DS10, DS11, DS12). Complementary to Table 5, Figure 13 shows the frequency distributions of the relative error for the front row sensors for test cases TC1 and TC3 for both simulation programs. Figure 16 in the Appendix shows the frequency distribution for front and back work and ceiling sensors for all five test cases. It is important to note that there currently does not exist a standard or common reference that suggests how high or low typical MBEs and/or RMSEs should be for a simulation to be considered 'reliable'. In order to help the reader interpret the results from Table 5 the authors therefore suggest error bands of plus/minus 15% and 35% for the MBE and RMSE, respectively. Values that fall out of this range are colored red bold in Table 5 and will be considered to be 'unusually high'.

One striking 'anomaly' for TC1 are the RMSE values for the front row of 110% for 3ds Max Design and 73% for Daysim. The reason for these large errors can be inferred from Figure

[5] The two errors are defined as follows: $MBE = \frac{1}{N}\sum_{i=1}^{N}\frac{(x_{test,i} - x_{ref,i})}{x_{ref,i}}$ and $RMSE = \frac{1}{N}\sqrt{\sum_{i=1}^{N}\left(\frac{(x_{test,i} - x_{ref,i})^2}{x_{ref,i}^{\,2}}\right)}$

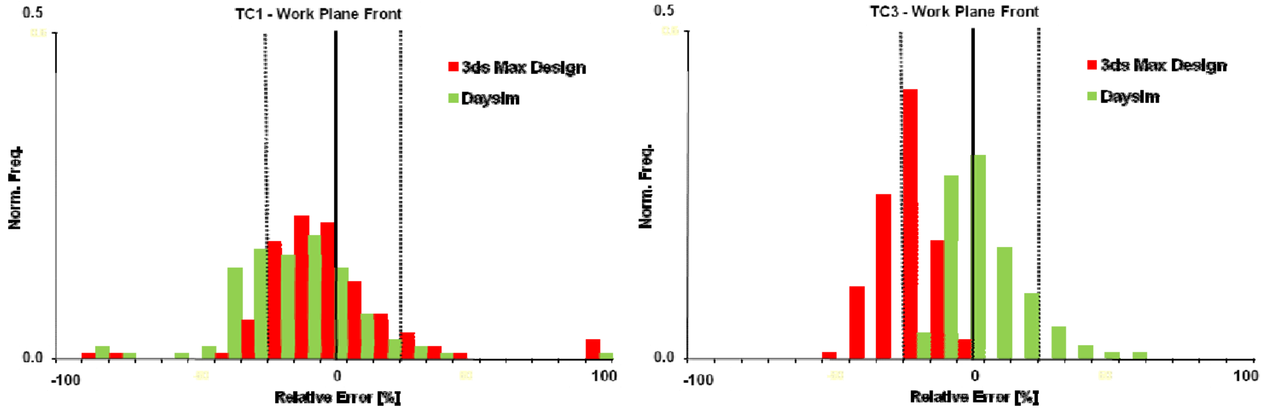
6. While the figure shows that both simulation programs succeed in reproducing the ups and downs of the front row sensor as it is moving in and out of direct sunlight, there are some small time shifts between the peaks. While it remains unclear what exactly caused these shifts, they result in some very large MBEs and RMSEs where the peaks do not fully overlap, i.e. according to the measurement the sensor is in direct sunlight but the simulation predicts otherwise and vice versa. For the MBEs these large errors average out but for the RMSEs they add up to the large values shown in Table 5. In order to demonstrate the magnitude of this 'shift effect' the numbers in brackets following the true RMSEs of the front work plane sensors for TC1 in Table 5 correspond to the RMSEs with the maximum relative error at each time step clipped to 100%. As one sees this brings the RMSEs for 3ds Max Design and Daysim down to more typical values of 28% and 31%, respectively. To further the argument, Figure 13(a) shows the frequency distribution of the relative errors for the central front row sensors for TC1. The figure reveals that most of the simulations (>60%) fall within a plus/minus 25% error band with respect to simulations and that about 4% of all sensors lie at the extreme ends of the spectrum and caused the high RMSE.

Another series of large errors in Table 5 were caused by the earlier discussed underestimation of the 3ds Max Design simulations for the translucent panel. Figure 13(b) shows the corresponding frequency distribution of the relative errors for the central front row sensor (DS2) for TC3.

Finally, there are a few out-of-range errors for 3ds Max Design and Daysim for the venetian blind test cases.

Table 5: Mean Bias Errors and Root mean Bias Errors for all test cases. MBEs (RMSEs) smaller than -15% (-35%) or larger than 15% (35%) are marked in bold red. Only sky conditions were considered for which the outside façade illuminance was over 5000 lux.

Test Case		**MBE [outside illuminance > 1000 lux]**				**RMSE [outside illuminance > 1000 lux]**			
TC.0 Outside Sensor	3dsMax	9				17			
	Daysim	7				14			
		Work Plane		**Ceiling**		**Work Plane**		**Ceiling**	
		Front	**Back**	**Front**	**Back**	**Front**	**Back**	**Front**	**Back**
TC.1 No Shading Device	3dsMax	11	6	-5	18	**110** (28)	29	28	28
	Daysim	-11	-4	-16	-7	**73** (31)	24	34	22
TC.2 Lightshelf	3dsMax	2	8	13	**20**	24	28	21	28
	Daysim	-10	-2	1	0	26	21	21	20
TC.3 Translucent Panel	3dsMax	**-22**	**-28**	-18	**-39**	25	30	22	**40**
	Daysim	4	10	8	1	15	21	20	17
TC.4 External Blinds	3dsMax	**20**	18	6	15	**41**	30	24	27
	Daysim	-6	-12	7	11	21	24	22	25
TC.5 Internal Blinds	3dsMax	-12	2	-12	-16	**49**	25	32	28
	Daysim	**-31**	-12	**-27**	-3	34	26	32	25



(a) (b)

Figure 13: Frequency distribution of the relative error for the front work plane sensor for (a) TC1 (a) and (b) TC3.

4 Discussion

4.1 Practical Considerations

The previous section presented how simulation results generated using two lighting simulation programs compare to measured data for five sidelit test cases. What are the implications of these results for a design practitioner? Under what circumstances can he or she now use these tools with confidence? An obvious but critical requirement for any simulation program to yield reliable results is that the user knows how to correctly use it, i.e. that he or she models a scene of interest in sufficient geometric detail, correctly specifies all scene materials and uses adequate simulation parameters. While a simple software can meaningfully support certain design decisions if the user understands its limitations, an advanced software may provide useless results if the user does *not* understand the software's underlying models and assumptions. The following discussion assumes that all lighting simulations are done by a qualified user.

Given this caveat, section 3 has shown that 3ds Max Design and Daysim both manage to approximate interior lighting levels in a variety of spaces based on direct and diffuse outside irradiances. How far can these results be generalized to other buildings, and are the observed modeling accuracies 'close enough'? This depends on what a user hopes to accomplish using simulations.

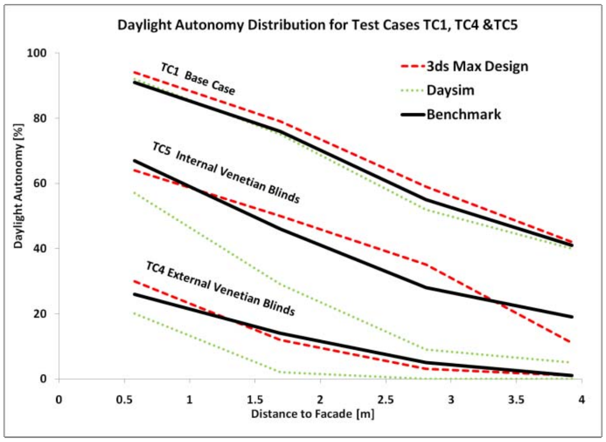
Most design practitioners currently use lighting simulation programs to visualize their designs for a qualitative analysis and client presentation purposes. Depending on the type of analysis it might or might not be important to the designer whether the simulated images are 'real' in terms of absolute luminance levels. The authors would argue that as a bare minimum for even the most rudimentary type of daylighting analysis the position of the sun in the sky has to be modeled accurately. Figure 6 shows that this is the case for 3ds Max Design and Daysim. Small differences such as the slight time shifts between measured and simulated peaks in Figure 6 have little or no impact on a visualization since they merely cause a slight shift of the shadow pattern within a scene.

For a quantitative glare analysis (Wienold and Christoffersen 2006), or in order to develop a feeling of how bright a space is actually going to be, it becomes important that absolute luminances are correctly modeled as well. Figure 7 shows that for spaces of low complexity (TC1 and TC2) both simulation programs correctly predict a large range of illuminances within a scene from over 20,000 lux for the outside façade sensor to less than 200 lux for the back ceiling sensor (Figure 7(d)). Since the interior surfaces in the test space are mostly Lambertian, a visualization of the scene could be modeled with comparable accuracy as the illuminances, especially under cloudy sky conditions. Under sunny sky conditions and when more detailed curved specular surfaces - such as venetian blinds - are introduced into a scene, visualizations and point calculations become less accurate and the effect of potential glare sources might be harder to predict. The authors believe that for such complex scenes and design questions experimentation with real world objects becomes a necessary, complementary tool to 'validate' computer-based lighting simulations. The resulting going back and forth between real world experiments and simulations is not a requirement introduced by the current state-of-the-art global illumination renderers – such as mental ray® or Radiance - but rather caused by our inability to reliably model and optically characterize complex fenestration systems.

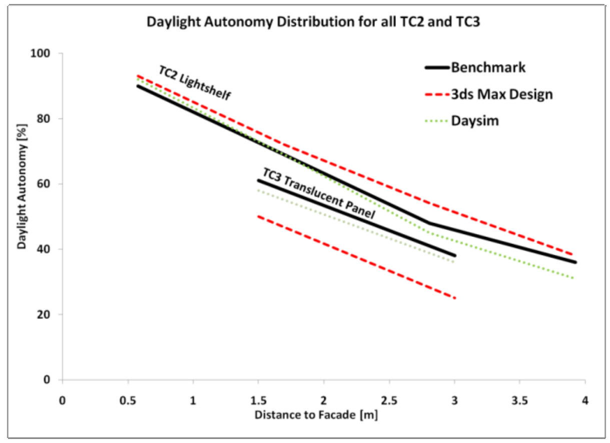
Practitioners are becoming increasingly interested in calculating absolute lighting levels at discrete positions in a space in order to describe the daylight in terms of a 'performance metric'. This interest in metrics is largely triggered by required and voluntary standards such as the US Green Building Council's LEED 2.2 green building rating system (USGBC 2006). Practitioners interested in using a lighting simulation to demonstrate compliance with the 8.1 LEED daylighting credit currently need to make sure that the simulation program they use supports the CIE clear and CIE overcast sky models. The clear sky is required for credit compliance under sunny sky conditions on an equinox day at noon, the CIE overcast sky is the reference sky for daylight factor calculations. The two CIE sky models are supported by 3ds Max Design and can be used in combination with Radiance using the *gensky* tool (Ward and Shakespeare 1998).

Clear and overcast CIE skies fall within the range of skies that can be modeled using the Perez sky model. The results from section 3 for cloudy and clear sky conditions therefore approximate how well 3ds Max Design and Daysim manage to model daylight factors and illuminances under CIE clear sky conditions and suggest that both programs can be used for demonstrating credit compliance under LEED 8.1.

Finally, looking ahead there is currently a strong push towards replacing the aforementioned 'static' daylight performance metrics which are based on a single sky condition with climate-based metrics that look at a large number of different sky conditions for a site under the course of a year (Reinhart, Mardaljevic and Rogers 2006). Section 3 has shown that both programs generally lend themselves for calculating these metrics since they are capable of simulating indoor illuminances under a range of sky conditions. Figures 14 and 15 show how well the two simulation programs would have calculated two climate-based metrics: Daylight Autonomy over 500 lux (DA_{500lux}) and Useful Daylight Illuminance between 100 lux and 2000 lux ($UDI_{100lux<2000lux}$) (Nabil and Mardaljevic 2005). DA corresponds to the percentage of time that a target illuminance level of 500 lux is maintained by daylight. $UDI_{100lux<2000lux}$ indicates the percentage of time for which interior illuminances stay within a target band of 100 lux to 2000 lux.



(b)



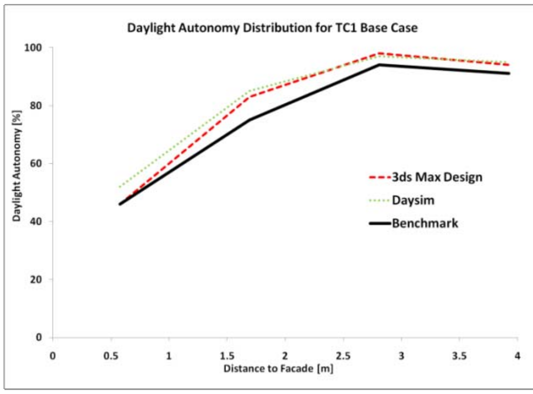
(b)

Figure 14: Daylight autonomies for the five test cases according to measurements and simulations.

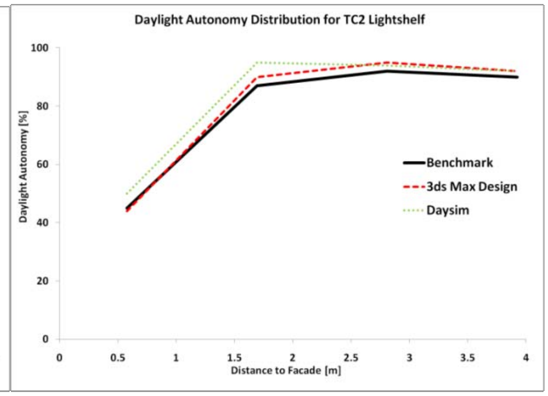
Figure 14 shows that the daylight autonomy distribution within the test case is very closely (within 4 percentage points) modeled by 3ds Max Design and Daysim for the base case with just a clear glazing (TC1). For the two intermediate test cases TC2 and TC3 as well as the external blinds (TC4) both programs model the daylight autonomy for each sensor point at least within 11 percentage points. It is only for the internal blinds (TC5) that Daysim daylight autonomy predictions diverge by up to 19 percentage points for the measurements whereas 3ds Max Design stays within respectable 8 percentage points with respect to the measurements.

Figure 15 shows the same results as the previous figure for the UDI metric. In this case simulation predictions lie for all test cases within 10 percentage points from the measurements except for the translucent panel (TC5) for 3ds Max Design (16 percentage points) and TC5 internal blinds for both programs (15 percentage points).

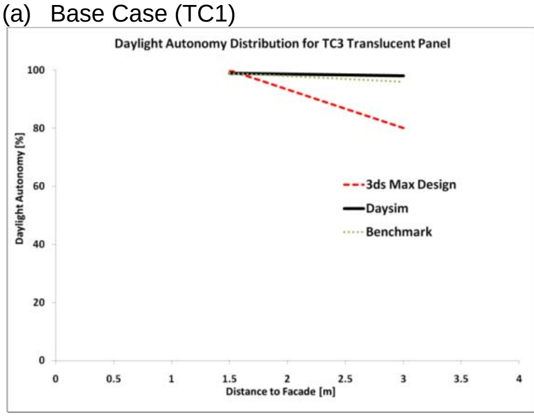
Are these simulation results ‘precise enough’? The answer depends on how sensitive a metric is. The daylight autonomy metric for the five test cases varies from 25% to 95% near the façade to 0% to 40% in the back of the space. Simulation errors of around 4 to 11 percentage points are small compared to this range. Also, the relative size of the daylight autonomy distributions for the five test cases is the same for the measurements and the two simulation programs meaning that a comparative analysis of the different test cases will lead to identical conclusions using measurements or either simulation program. Based on this the authors suggest that the simulation accuracy is sufficient to support design decisions regarding spaces of comparable complexity as the five test cases. One case of concern might be the very low Daysim daylight autonomy predictions for the internal venetian blinds. This test case is briefly revisited below. The UDI distributions for the five test cases tend to lie loser together than the DA distributions, and the simulated UDI distributions tend to lie closer to the measured UDI distributions. For this metric the only simulation results of concern are the low value in the back of the space for the translucent test case (TC3) for 3ds Max Design and the two high UDIs predicted near the façade for TC5 by both programs.



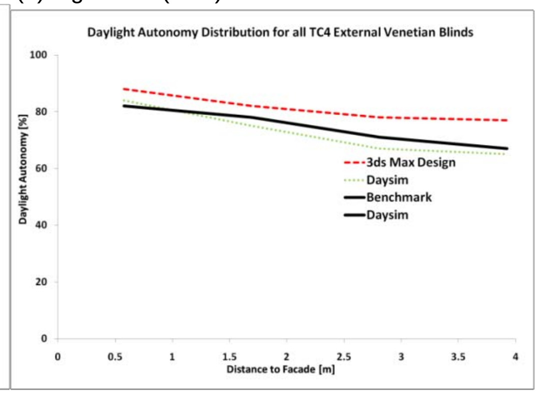
(a) Base Case (TC1)



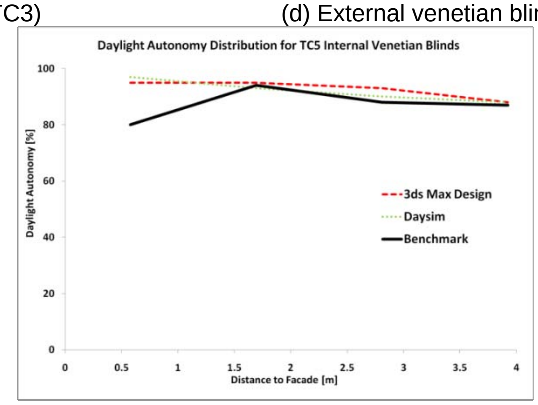
(b) Lightshelf (TC2)



(c) Translucent panel (TC3)



(d) External venetian blinds (TC4)



(e) Internal venetian blinds (TC5)

Figure 15: Useful daylight illuminance distributions for the five test cases according to measurements and simulations.

4.2 Modeling movable shading devices

Section 3 has shown that geometrically detailed elements such as venetian blinds are difficult to model accurately. In this context it is interesting to note that it is not necessarily the global illumination engine – be it Radiance or mental ray® – that is intrinsically incapable of modeling these elements but our inability to fully characterize such complex fenestration systems optically. Another, more decisive difficulty when it comes to reliably evaluating the daylight in a space with venetian blinds is that these are *movable* shading devices that are manually and/or automatically readjusted by building occupants in a manner that we are only just starting to understand (Reinhart and Voss 2003). The uncertainly introduced by occupant behavior is typically a lot larger than errors within the lighting calculation.

4.3 3ds Max Design and Daysim/Radiance

While the overall focus of this study is to compare both 3ds Max Design as well as Daysim simulations to measurements, a reader's natural tendency might be also to compare the performance of both programs and to judge 'which one is better'? This subsection aims to review the capabilities of both programs.

First of all, these results suggest that 3ds Max Design is a viable tool to base daylighting design decisions on. This is an important statement since Daysim and Radiance are really the only programs that have thus far been rigorously validated. This finding is actually not that surprising since both programs are based on very comparable models: They use the same sky model and a backward raytracer for the global illumination simulation.

Considering the relative performance between 3ds Max Design and Daysim one should keep in mind that Daysim is a limited version of Radiance Classic since (a) it does not support the full range of material modifiers within Radiance and (b) it approximates direct solar contributions at any given time step via interpolation between neighboring daylight coefficients (Bourgeois et al. 2008). Daysim has been developed to be a practical tool to develop indoor illuminances under multiple sky conditions when Radiance Classic could not do it within a reasonable time frame[6]. The question of simulation time is therefore closely related to what one wants to calculate.

For a simulation under a single sky condition 3ds Max Design should be compared to Radiance Classic. Given that the observed simulation times for the daylighting test cases under a sunny sky were 0.6 to 4 hours for Radiance Classic compared 12 seconds for 3ds Max Design on a comparable computer it is fair to state that 3ds Max Design is significantly faster than Radiance Classic for daylight factor or CIE clear sky simulations.

Daysim simulations of the five test cases took between 3 and 15 hours. For an annual daylight simulation that involves multiple skies 3ds Max Design simulation times would actually take about the same time or longer as the tool would have to calculate indoor illuminances under all sky conditions individually. For an hourly time step annual simulation the calculation time would be around 15 hours[7]. For a 5 minute time step calculation which might be required for an annual glare analysis (Wienold 2007) or for modeling occupant use of personal controls in a space (Reinhart 2004) the calculation would take about a week. An obvious way to sidestep these long simulation times in 3ds Max Design would be to implement a daylight coefficient approach into the software.

4.4 Other lighting programs

As previously mentioned there is a growing number of design practitioners who are looking for physically accurate results in their lighting simulation software. This paper has shown that 3ds Max Design and Daysim can be used to support daylighting related design decisions and that the new NRC daylighting test cases constitute a useful tool to benchmark lighting simulation software. The outcomes of such benchmarking exercises do not only provide useful guidance for software users but they can also help software developers to identify bugs and previously unknown weaknesses within their products. An example for this are the results for the translucent panel test case for 3ds Max Design. Working with the test cases the authors found the five NRC daylighting test cases reliable but would have found it useful to have additional parameters along with the existing data. Future versions of such test cases should for example include high dynamic range (HDR) images of outside sky luminance distributions along with HDR inside views from representative ceiling and work plane sensors in order to allow a developer to better separate sky model errors from global illumination errors. Such a data set

[6] The new *rtcontrib* routine within Radiance offers an alternative Radiance based daylight coefficient approach.

[7] 12 seconds per sky condition x 4380 daylit hours in a year = 14.6 hours

would also help to quantify typical error ranges for lighting visualizations that are used for glare evaluation purposes.

It is the hope of the authors that more software developers will use the NRC daylighting test cases and other comparable data sets to validate their programs against and that over time such experimental validations will become a formal requirement for any software that is used to demonstrate credit compliance under LEED and other rating systems. ASHARE/ANSI Standard 140 already provides a similar set of requirements for building energy simulation software (ASHRAE 2007).

5 Conclusion and Outlook

This study found that 3ds Max Design and Daysim can be used to support daylighting related design decisions in scenes of comparable complexity as the five NRC daylighting test cases. This is good news for design teams interested in using physically based lighting simulations for further design analysis as they now have more than one simulation engine to choose from. Given the rising interest in physically accurate lighting simulations the authors expect that other simulation programs will soon go through comparable experimental validation exercises using either the NRC daylight test cases or other data sets and that the group of validated programs is going to increase in the near future. In order to facilitate this process the NRC daylight test cases (measurements and SketchUp files) as well as all 3ds Max Design and Daysim files used to produce this report will be shortly made publicly available.

As mentioned several times throughout the report, the remaining challenges when it comes to evaluating the daylighting for a space using advanced simulations are (a) to identify suitable daylight performance metrics and benchmarks, (b) refine occupant behavior models that mimic how one or several movable shading devices are operated within a space, and (c) develop quality controlled databases for complex fenestration systems to increase the range of daylighting technologies that can be reliably evaluated.

Acknowledgement

This work has been funded by the Autodesk Media and Entertainment Division and the National Research Council Canada – Institute for Research in Construction (NRC-IRC) under NRC-IRC contract number B3241. The authors are indebted to Chantal Arsenault and Roger Marchand for preparing the NRC Daylighting Laboratory for the validation measurements and to Anca Galasiu for helping with some of the early results analysis. We are further indebted to Kalwall (Keller Company) for letting us use the measurements from an earlier validation study again for this study as well as to John Mardaljevic, Guy Newsham and Greg Ward for providing valuable comments on earlier versions of this paper.

References

Aizlewood, M. E. (1993). "Innovative daylighting systems: An experimental evaluation." Lighting Research & Technology 25(4): 141-152.

ASHRAE (2007). ANSI/ASHRAE Standard 140-2007 Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs, American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Bleicher, T. ((last accessed in December 2008)). "Radiance plug-in for SketchUp www.bozzograo.net/radiancewiki/doku.php/input:exporters:su2rad."

Bourgeois, D., C. F. Reinhart and G. Ward (2008). "A Standard Daylight Coefficient Model for Dynamic Daylighting Simulations." Building Research & Information 36(1): 68 - 82.

Jarvis, D. and M. Donn (1997). Comparison of computer and model simulations of a daylit interior with reality. 5th International Building Performance Simulation Association (IBPSA) Conference.

Mardaljevic, J. (1995). "Validation of a Lighting Simulation Program under Real Sky Conditions." Lighting Research & Technology 27(4): 181-188.

Mardaljevic, J. (2000). "The BRE-IDMP dataset: a new benchmark for the validation of illuminance prediction techniques." Lighting Research & Technology 33(2): 117-136.

mental-images (2007). mental ray(R) Functional Overview Version 1.5, <http://www.mentalimages.com/fileadmin/user_upload/PDF/mental_ray_Functional_Overview.pdf> Berlin.

Nabil, A. and J. Mardaljevic (2005). "Useful Daylight Illuminance: A New Paradigm to Access Daylight in Buildings." Lighting Research & Technology 37(1): 41-59.

P R Tregenza, I. M. W. (1983). "Daylight Coefficients." Lighting Research & Technology 15(2): 65-71.

Reinhart, C., J. Mardaljevic and Z. Rogers (2006). "Dynamic Daylight Performance Metrics for Sustainable Building Design." LEUKOS 3(1): 1-20.

Reinhart, C. F. (2004). "LIGHTSWITCH 2002: A model for manual and automated control of electric lighting and blinds." Solar Energy 77(1): 15-28.

Reinhart, C. F. (2006). Tutorial on the Use of Daysim Simulations for Sustainable Design, Software Documentation. Ottawa, Canada, National Research Council Canada Institue for Research in Construction.

Reinhart, C. F. and M. Andersen (2006). "Development and validation of a Radiance model for a translucent panel." Energy and Buildings 38(7): 890-904.

Reinhart, C. F. and A. Fitz (2006). "Findings from a survey on the current use of daylight simulations in building design." Energy and Buildings 38(7): 824-835.

Reinhart, C. F. and K. Voss (2003). "Monitoring Manual Control of Electric Lighting and Blinds." Lighting Research & Technology 35(3): 243-260.

Reinhart, C. F. and O. Walkenhorst (2001). "*Dynamic RADIANCE-based Daylight Simulations for a full-scale Test Office with outer Venetian Blinds*." Energy & Buildings 33(7): 683-697.

SketchUp, G. (last accessed December 2008). "SketchUp Version 7 http://sketchup.google.com/."

USGBC, U. G. B. C. (2006). "LEED-NC (Leadership in Energy and Environmental Design) Version 2.2." from www.usgbc.org/LEED/.

Ward, G. and F. Rubinstein (1988). "A New Technique for Computer Simulation of Illuminated Spaces." Journal of the Illuminating Engineering Society 1: 80-91.

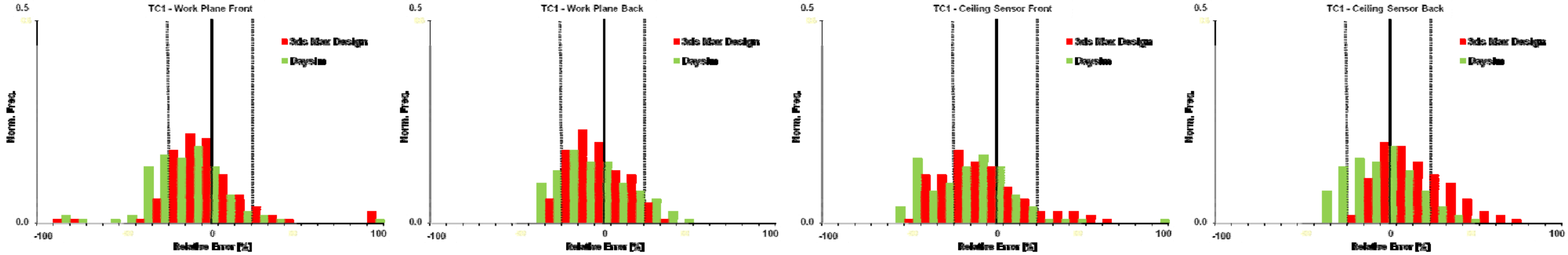
Ward, G. and R. Shakespeare (1998). Rendering with RADIANCE. The Art and Science of Lighting Visualization, Morgan Kaufmann Publishers.

Wienold, J. (2007). Dynamic simulation of blind control strategies for visual comfort and energy balance analysis. Building Simulation 2007, Beijing, China.

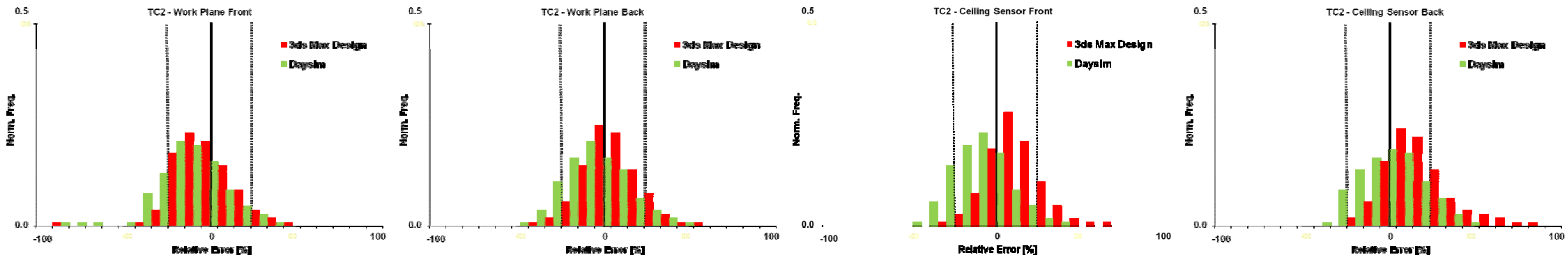
Wienold, J. and J. Christoffersen (2006). "Evaluation methods and development of a new glare prediction method for daylight environments with the use of CCD cameras." Energy and Buildings 38(7): 743-757.

Appendix

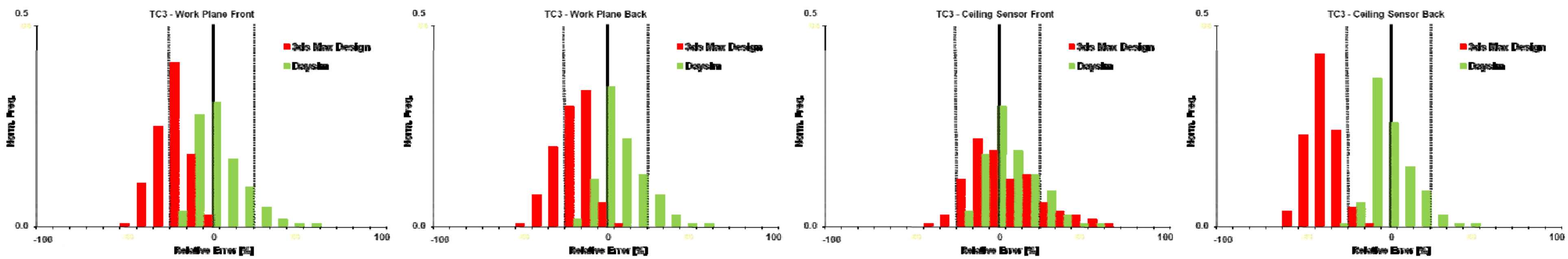
TC1 – Base geometry



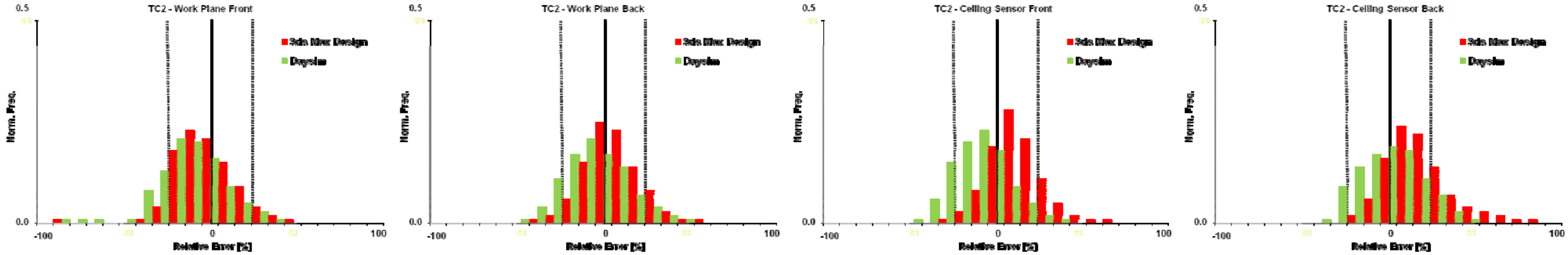
TC2 - Lightshelf



TC3 – Translucent Panel



TC4 – External Venetian Blinds



TC5 – Internal Venetian Blinds

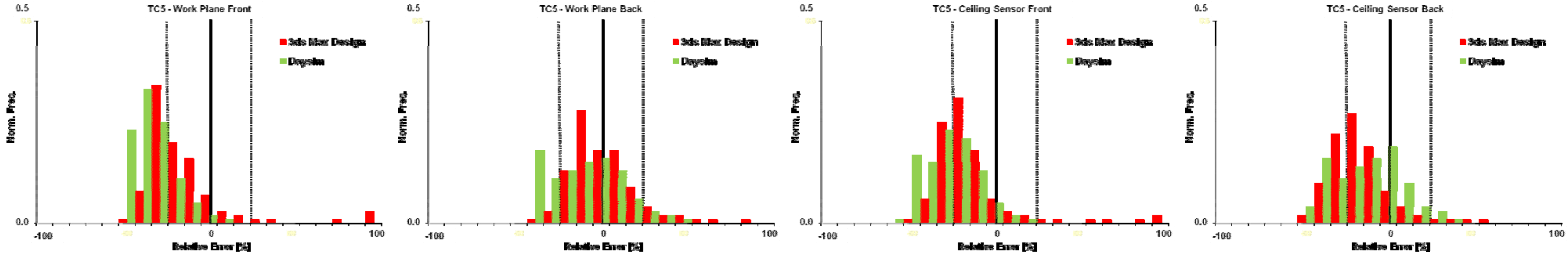


Figure 16: Frequency distribution of relative errors for all five test cases.