Simple tool to evaluate the impact of daylight on building energy consumption

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Abstract

This paper presents a simple building simulation tool for integrated daylight and thermal analysis. The tool is capable of importing the thermal and visual properties for different glazings and shading positions from the Window Information System (WIS) program. A coupled ray-tracing and radiosity methodology is used to derive the daylight levels for different sky conditions. Both detailed daylight distribution for a particular day and time and hourly discrete values on a yearly basis may be obtained. For an integrated simulation the hourly daylight levels are fed into an existing simple thermal simulation program capable of calculating energy demand and the indoor environment. Straightforward control systems for general and task lighting systems have been implemented together with a shading control strategy that adjusts the shading according to the indoor operative temperature, the risk of glare and the profile angle of the sun. The implemented daylight calculation method allows for shades from the window recess and overhang, and for distant shades blocking the sky vault. Comparisons with the ray-tracing program Radiance show that the accuracy of this approach is adequate for predicting the energy implications of photoresponsive lighting control. The amount of input is small, which makes the tool useful for integrated daylight optimisation in the early design process.

Keywords: Simulation; Daylight; Validation; Radiosity; Integrated design; Building design

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1. Introduction

Energy performance and indoor environment have become increasingly important in building design. Building developers and designers are straining to produce end-user buildings with a low energy consumption and high indoor environmental performance. This has lead to a growing awareness that to achieve low-energy buildings with satisfactory indoor climate the designer has to be aware of the consequences of critical design decisions as early as possible in the design process to obtain a good final whole-building cost-benefit ratio (Petersen and Svendsen, 2008). In this context integrated simulation of daylighting and artificial lighting plays a significant role on energy consumption, indoor environment and environmental impact as the fenestration system influences heat loss, solar gains and daylight penetration (Lee et al., 1998; Jenkins and Newborough, 2007; Tzempelikos and Athienitis, 2007).

Sparked by innovations in dynamic fenestration and shading systems and increasingly sophisticated characterizations of glazings and shading devices (van Dijk and Oversloot, 2003; Andersen and de Boer, 2006; Window 6.1 Research Version, 2008) some detailed simulation programs like ESP-r (University of Strathclyde, 2008), and EnergyPlus (US Department of Energy, 2008) now link daylight and thermal simulation in an integrated manner (Clarke and Janak, 1998; Crawley et al., 2002). However to run these programs they require expert knowledge and large amounts of input data for even the simplest simulation, rendering them impractical in the early design stage when information is scarce. This calls for tools that are capable of rapid and dynamic calculation of the impact of fenestration and shading provisions on lighting demand, cooling demand and occupant glare.

Such rapid whole-year algorithms are starting to emerge (Lehar and Glicksman, 2007; Walkenhorst et al., 2002), but they still lack interactivity with the thermal domain. Franzetti et al. (2004) implemented a daylighting software module with a thermal model, but the validity of the model was restricted to internal working plane illuminances below 1000 lux. Athienitis and Tzempelikos (2002) developed an integrated model based on clear and overcast sky formulations for external illuminances and radiosity for internal illuminances. This approach, however, assumes that direct light is diffused in the shading devices and that incident diffuse light on the outside of the window is transmitted uniformly. The tool described in this article employs the radiosity method for internal daylight reflections, while the incident initial light is calculated by tracing the rays emanating from the sky to the room surfaces. This gives a reasonable balance between accuracy and calculation time.

The tool encompasses a fully integrated thermal and daylighting simulation with detailed hourly output of the daylight level, the electrical energy consumption for lighting, heating load, cooling load and indoor operative temperature. The main objective is to help design professionals with interest in - but no expert knowledge of - daylighting to develop climate-responsive daylighting design concepts, to optimize façade layout and orientation with respect to daylight and energy use and to quantify energy savings from manual and photocell controlled dimming. The amount of input is small which renders the tool practical in the early stages of design or as simulation foundation for an integrated design process where it is essential to quantify and create awareness of the consequences of design decisions (Petersen and Svendsen, 2008).

An existing simplified thermal simulation tool BuildingCalc (Nielsen, 2005) and a daylight simulation tool LightCalc (Nielsen et al., 2005) formed the starting point for the work, the BC/LC tool. In the following, the implemented sky model and algorithms for externally and internally reflected light are described together with the shading control strategy and the coupling procedure. The daylight simulation tool is validated by comparison with Radiance (Ward and Shakespeare, 1998) and the impact on energy demand is discussed.

2. Calculation procedures

2.1. External light distribution

External daylight may be divided into direct light from the solar disc, diffuse light due to the scattering properties of the atmosphere, and diffuse light reflected from the ground and surroundings.

The diffuse light is modelled using the approach in Robinson and Stone (2006) and summarized here.

An upper sky dome for atmospheric light and a lower (inverted) sky dome for ground reflections (one above and one below the horizontal plane) are used to model diffuse light. Each sky vault is divided into 145 patches using a discretization scheme proposed by Tregenza (1987). Each patch subtends a similar solid angle Φ (Sr), which enables every patch to be treated as a point source with insignificant error. The sky vault is divided into seven azimuthal bands of equal angular height ($\sin \gamma_{\mathrm{i,max}} - \sin \gamma_{\mathrm{i,min}}$), in which the azimuthal range $\Delta\alpha$ increases towards zenith (12°, 12°, 15°, 15°, 20°, 30°, 60°).

$$\Phi_i = \Delta\alpha_i \left(\sin \gamma_{i,\max} - \sin \gamma_{i,\min}\right) \tag{1}$$

Let L be the luminance (lm m^{-2} Sr^{-1}) of the i'th patch, ξ the mean angle of incidence (rad), σ ($0 \leq \sigma \leq 1$) the visible proportion of the patch, then the illuminance E_{sky} on an external plane due to diffuse light from the sky vault is expressed as:

$$E_{\mathrm{sky}} = \sum_{i=1}^{145} \left(L \Phi \sigma \cos \xi\right)_i \tag{2}$$

Let E_{n} be the direct normal illuminance and ξ the incidence angle, then the illuminance on an external inclined plane due to direct light is:

$$E_{\mathrm{sun}} = E_{\mathrm{n}} \cos \xi \tag{3}$$

Having determined the light sources, the reflecting ground can be represented as a luminous up-side down sky with constant brightness. Let L^* be the ground patch luminance, then the illuminance due to reflected light E_{ground} is expressed as:

$$E_{\mathrm{ground}} = \sum_{j=i}^{145} \left(L^* \Phi \sigma \cos \xi\right)_j \tag{4}$$

where L^* is expressed as a function of the total horizontal diffuse illuminance E_{sky} and the direct illuminance E_{sun} on a horizontal plane and the mean ground reflectance ρ (albedo):

$$L^* = \frac{\rho}{\pi}\left(E_{\text{sun}} + E_{\text{sky}}\right) \tag{5}$$

Figure 1 shows the principle of how the luminosity of the sky may vary while the ground luminosity is uniform.

The European Solar Radiation Atlas (Scharmer and Greif, 2000) recommends the use of the Perez all-weather model (Perez et al., 1993) or the Muneer model (Muneer et al., 1998) for modelling anisotropic sky radiation. The Perez model is chosen because it is amenable to implementation in a computer program while maintaining good overall performance. The luminance of a sky point L_i is given here:

$$L_i = \frac{lv_i dh}{\sum_{j=1}^{145}\left(lv\Phi\cos\xi\right)_j} \tag{6}$$

where the relative luminance, lv, defined as the ratio between the luminance of the considered sky point and the luminance of an arbitrary reference sky point (usually the zenith luminance), is normalized to diffuse horizontal illuminance dh as recommended by Perez et al. (1993). Diffuse horizontal and direct normal illuminances are obtained from measured horizontal and direct normal irradiances respectively by a luminous efficacy η given in Perez et al. (1990).

The visible proportion σ is calculated by establishing a 10x10 grid of each patch and evaluating the visibility of each grid point for every internal surface. The incidence angle ξ is calculated from the weight-averaged visible proportion of the sky patch. Thus σ is a function of both distant objects (other buildings, the landscape) and near shades like the window recess and overhang.

Reflected light from opposing building façades is treated in two ways. For building surfaces below the horizontal plane, their reflectances are part of the average albedo. For buildings that cover parts of the upper sky dome, the algorithms for incident light on inclined surfaces in Perez et al. (1990) are used. The incident light on the opposing building surface E_{build} is then multiplied by the specified reflectance of the building ρ_{build} ignoring any specular effects or interfaçade reflections. The sky patch luminance $L_i^{'}$ then substitutes the luminance of the covered patch with respect to the visible proportion σ: $L_i^{'} = L_i\sigma_i + E_{\text{build}}\rho_{\text{build}}\left(1-\sigma_i\right)$. Thus only one ‘bounce’ of light is taken into consideration and we ignore the interreflections that deep urban canyons produce.

2.2. *Internal daylight distribution*

The calculation of the internal distribution of light was based on the luminous exitance method. This method is analogous to the radiosity method, in that all the restrictions and assumptions are the same. Internal subsurfaces hit by transmitted direct and diffuse light act as light sources, with the initial exitance *Mo,* if we assume these surfaces have Lambertian optical characteristics and reflect incident light perfectly diffusively and ignore any specular properties. The methodology and implementation of the daylight distribution algorithms are described in Park and Athienitis (2003).

2.3. *Coupling of external and internal light distribution*

Diffuse light

To establish the initial light exitance *Mo* (lm m^{-2}) of a subsurface the amount and the direction of the light and the reflectance of the surface have to be known. Therefore the external and internal light distributions were coupled in a simple ray-tracing approach that assumes the luminance of the sky hemisphere and ground hemisphere patches can be considered as point sources.

For diffuse sky and ground light penetrating into the room, the exitance for each *k*’th internal subsurface was calculated using (2) and (4) multiplied by the light transmittance τ and the surface reflectance ρ:

$$Mo_k = \rho_k \left(\sum_{i=1}^{145} \left(L\Phi\sigma \cos\xi\tau \right)_i + \sum_{j=1}^{145} \left(L^{*}\Phi\sigma \cos\xi\tau \right)_j \right) \tag{7}$$

The light transmittance is calculated by the WIS program (WinDat, 2006), see section 2.4, but WIS only calculates uni-directional, profile-angle dependent transmittances. The profile angle θ is defined as the line of elevation (usually to the sun) projected unto the vertical normal plane of a surface. We may also name it the perpendicular incidence angle on a vertical surface. For clear glazings and shading systems with isotropic optical properties we use the profile-angle dependent transmittances directly with corresponding incidence angles. For anisotropic optical shadings like blinds we multiply the transmittance with the profile angle so τ is replaced with τ_θ in (7) and (8).

Direct light

For direct solar light a different approach is applied. It is evident that all direct light transmitted through the glazing hits a subsurface. Subdividing the internal surfaces however may result in false prediction of the amount of incoming direct light. Let E_{dir} denote the incident sun light on the window plane obtained by (3), A_{g} the glazing area, A_k the area of the k'th internal subsurface and m the total number of internal subsurfaces. If we define a normalization factor $\chi = E_{\text{dir}} A_{\text{g}} \tau \Big/ \sum_{k=1}^{m} E_{\text{n}} A_k \tau \cos \xi_k$ then the initial exitance Mo of the k'th subsurface is written:

$$Mo_k = E_{\text{n}} \rho_k \tau \cos \xi_k \ \chi = E_{\text{dir}} A_{\text{g}} \rho_k \tau \cos \xi_k \left(\sum_{k=1}^{m} A_k \cos \xi_k \right)^{-1} \tag{8}$$

When the direct light is transmitted through the glazing, some of the direct light may be transformed into diffuse light in a diffusing device, e.g. blinds placed in conjunction with the glazing. This effect is taken into consideration by calculating the light contribution from sun, sky, and ground on the window plane by using (2), (3), and (4). The exitance of the inner glazing surface Mo_{g} is determined by multiplying the total light contribution by the light transmittance for direct light that diffuses when it passes the glazing+shading $\tau_{\text{dir}\rightarrow\text{dif}}$. This light transmittance is calculated by WIS, see section 2.4.

$$Mo_{\text{g}} = \left(E_{\text{dir}} + E_{\text{sky}} + E_{\text{ground}} \right) \tau_{\text{dir}\rightarrow\text{dif}} \tag{9}$$

Devices that redirect the incoming light, e.g. a specular light shelve are modelled using a simple implementation. It is achieved by setting a special redirecting light transmittance τ_{redir} to a value between 0 and 1 where 0 means that no light is redirected and 1 that all incoming light is redirected. This means that for an incoming ray of light with a profile angle θ the following applies: $\tau_{\theta} + \tau_{\mathrm{dir}\rightarrow\mathrm{dif},\theta} + \tau_{\mathrm{redir},\theta} = 1$ The inclination angle β of the slat or light shelve determines the reflection angle. Only fully specular devices are considered and any specular interreflections between slats and between the slats and glazing are ignored. On Figure 2 the principle is illustrated.

2.4. Light transmittances

A critical element in the daylight calculation routine is the light transmittance of the combined glazing/shading system. For this purpose the European software tool called WIS (WinDat, 2006; van Dijk and Oversloot, 2003) is used. This tool implements algorithms from the standard ISO 15099 (ISO, 2003) capable of calculating the light transmittance of a transparent system for both direct and diffuse light.

WIS calculates the thermal and solar performance of multilayered window systems, allowing the user unlimited combinations of glazing and solar shading devices. This makes WIS a very powerful tool for evaluating various integrated daylight designs. Currently the improvement and verification of WIS, and its database format and database population are the responsibility of the EU Thematic Network WinDat, which consists of major European research institutions and manufacturers of window components (glazings, solar shadings, etc.).

The output from a WIS calculation is in the format of a text file. The file include the light transmittances and solar energy transmittances for different solar profile angles (-90° to 90° at 10° increments), and may be loaded seamlessly into the BC/LC tool. If the shading device has multiple shading positions, e.g. Venetian blinds, the user may generate and load files for every position required. The tool will linearly interpolate between the transmittance data loaded, thus making the number of loaded positions a question of desired accuracy.

Because the employed method of calculating incident light on internal subsurfaces is equivalent to a ray-tracing technique, the WIS transmittance for direct light is employed for both diffuse and direct light. WIS cannot yet handle specular shading devices, e.g. light shelves or light redirecting devices. The tool described in this article, however, accepts transmittance data for redirecting devices obtained in other ways, e.g. from Radiance.

3. Control strategies

3.1. Thermal simulation

The simplified thermal model in the BC/LC tool is described in detail in Nielsen (2005). It is capable of evaluating the thermal indoor environment and heating and cooling loads in a building with very few input parameters while providing the option of sophisticated system controls. The model is based on a two-nodal equation system with one node representing the air temperature and one the internal temperature of the constructions. The mean surface temperature represents the internal surfaces where heat is exchanged with the indoor air and the effective heat capacity of the constructions. The equation system has an analytical solution and by the end of each time step the temperatures are calculated based on the initial temperatures of the time step. The systems control strategy is ideal yet satisfactory for quick design suggestions. During each time step systems are activated to control the risk of glare and the indoor air temperature which changes the analytical solution and causes the equation system to be solved several times within a time step to achieve a given set-point.

3.2. Artificial lighting

The artificial lighting system can be divided into general and task lighting which may be defined and controlled separately. Both systems are defined by the power consumption of the lighting fixtures in W/m^2 when providing an illuminance of 100 lux, and the minimum (standby) power consumption. The relationship between power consumption and illuminance on the workplane is assumed to be linear and is depicted on Figure 3. The values for power density and corresponding illuminance are often supplied by the producers of lighting fixtures, and the maximum illuminance is calculated using the maximum power density.

For each time profile, the implemented control strategies are ‘always on’, ‘always off’, ‘on-off’, and ‘dimming’. The tool evaluates the hourly incoming daylight at two arbitrary points determined by the user and switches the lighting systems on and off or dims them according to the chosen lighting control strategy. The ‘on-off’ control switches between the maximum and minimum power consumption when the daylight level is below or above the illuminance setpoint. The ‘dimming’ control interpolates linearly between the maximum and minimum power consumption in order to meet the specified setpoint. Electrical losses in the ballast must be included in the power density.

3.3. Shading

The task of the shading in an office room is multipurpose: it should block direct sunlight to minimize the risk of glare and high contrasts which are discomforting to the occupants while allowing the maximum amount of daylight to enter the room on overcast days. At the same time it should block excessive solar gains to avoid overheating while preserving a good view to the outside. Some shading devices are also capable of controlling and redirecting the incoming direct sunlight and pass it on to the room as diffuse light. To accommodate the various demands the BC/LC tool is provided with a shading control based on a two-conditional strategy and the cut-off angle.

When any of the two conditions: indoor operative temperature or risk of glare are exceeded the cut-off strategy is activated. In the case of adjustable blinds they are lowered and adjusted to the slat angle where the direct sun is just blocked, see Figure 4. This strategy maximizes the incoming amount of daylight while blocking the main contributor to glare and indoor overheating. In the case of screens the control is limited to screen up or screen down. The cut-off angle β is calculated from:

$$\beta_{\mathrm{cutoff}} = \arcsin\left(\frac{d\cos\theta}{w}\right) - \theta \tag{10}$$

The distance between two slats is defined by d (m), θ is the profile angle of the sun (degrees), and w is the width of the slats (m).

3.4. Glare

To calculate the risk of glare we use a daylight glare probability index which is proposed by Wienold and Christoffersen (2006). The DGP index is defined in the interval [0.2; 0.8] and is directly correlated with the percentage of disturbed persons. According to Wienold and Christoffersen (2006) the correlation between the linear function of vertical eye illuminance and DGP is stronger than all other tested functions. If E_v denotes the vertical eye illuminance (lux), the daylight glare probability is then written:

$$\mathrm{DGP} = 5.87 \times 10^{-5} E_\mathrm{v} + 0.16 \tag{11}$$

This means that DGP values of 0.2 (20% disturbed) approximately corresponds to a vertical eye illuminance of 700 lux.

3.5. Thermal simulation coupling

The integration of the daylight and thermal domain requires a sophisticated coupling to calculate the incoming daylight, the effect of shading on daylight levels, and electrical lighting consumption and indoor air temperature. Figure 5 gives a schematic overview of the coupling. The algorithm controls the shading device by linking the incoming daylight with the effect of shading on daylight levels, artificial lighting load and indoor air temperature. This is achieved by pre-calculating the hourly daylight levels in the room without shading, initiate the thermal simulation, evaluate the hourly indoor operative temperature with respect to the cooling setpoint, possibly lower the shading and adjust the slat angle (for blinds) to cut off direct sunlight, and calculate the daylight levels again. If the operative temperature still exceeds the cooling setpoint, other measures like venting, increased ventilation, and mechanical cooling are employed in that order.

4. The tool

The tool may be used in two ways: 1) for detailed daylight distribution in a room for a particular day, time and sky luminance distribution and 2) coupled with the thermal domain to quantify the impact of daylight on the building energy consumption. An example of output from a detailed daylight simulation is depicted on Figure 6 showing the daylight factor contour lines from a CIE standard overcast sky with internal subsurfaces the size of 0.5 x 0.5 m.

The output from a coupled simulation encompasses hourly values for the daylight level in two arbitrary points and the artificial lighting load together with results from the thermal domain: heating and cooling demand, ventilation airflow, indoor operative temperature, shading factor, PMV and PPD. The results are presented graphically in figures and by tables. Figure 7 depicts some of the results from a coupled simulation. A whole-year simulation with retractable blinds takes approx. 6 minutes on a laptop with a Pentium M processor running at 1.86 GHz and 2 GB of RAM. The subsurface size was set to 2 x 2 m, because this has a significant impact on simulation speed and only introduces an error in the magnitude of 1% compared to 0.5 x 0.5 m. Figure 7 shown how the tool can quantify the implications of exploiting daylighting and reducing the artificial lighting load with photoresponsive controls.

The tool is programmed in Matlab (MathWorks, 2008) and uses a graphical user interface to get input from the user and to provide results from simulations. Its simple input makes it easy and quick to estimate the impact on building energy consumption for different daylight and shading designs. The program exists both in a version to run in Matlab and a version to run as a windows program for people who do not have Matlab. The former includes all the source code while the latter requires the installation of Matlab runtime libraries. Both program versions are available from the web address http://www.dtu.dk/centre/BFI/energirigtigtbyggeri/integrateddesign.aspx or by contacting the corresponding author.

5. Validation

Of the numerous lighting simulation programs available, Radiance has been extensively validated and repeatedly surpassed competing programs in terms of both functionality and accuracy. For these reasons, we chose Radiance as our reference model. It is a back-ward ray-tracer and was developed by Greg Ward at Lawrence Berkeley National Laboratories. It yields physically based simulations of indoor illuminance and luminance distributions for diffuse, specular and partly specular materials. We use the Radiance version 3.9 from the Learnix bootCD version 5.0.1 which is available from http://luminance.londonmet.ac.uk/learnix/ The validation was carried out with four setups: clear glazing, blinds, screen and opposite building façade. All four setups is validated with the anisotropic Perez sky model because it is used for the coupled simulations, but we also test the CIE standard overcast sky on a clear glazing because it is often used to quantify daylight design. The Perez sky is generated with the gendaylit package for Radiance developed by Delaunay (1994).

The test room has a south facing window and dimensions as specified on Figure 8. The selected date for the anisotropic Perez sky is September the 21st at 3 p.m. because it involves complex calculation of solar position, incidence angles and cut-off slat angles. The external irradiances are obtained from the Danish Design Reference Year.

Generally we use the default stochastic ray-sampling in Radiance, but the blinds were modelled with the *mkillum* program which is generally the recommended approach for treating blinds (Ward and Shakespeare, 1998). Table 2 contains input parameters to Radiance and Mkillum which are diverging from the default values.

Figure 9 depicts the daylight factor and relative error computed with Radiance and the BC/LC tool using the CIE standard overcast sky. All the measuring points are in good agreement and the relative error is below 6%. The illuminance levels with the Perez sky and a clear glazing on Figure 10 also show good agreement with relative errors below 6%. The same good agreement is found with the lowered screen on Figure 11 where the largest relative error is 8%. For more complex shading devices like the lowered and cut-off adjusted external dark Venetian blinds on Figure 12 the largest relative error is 35%. The error is due to the uni-directional light transmittances from WIS. This influences the direct light penetrating the blinds and the diffuse light distribution on the inside of the blinds. This calls for more accurate characterization of the properties of complex shading devices.

Figure 13 depicts the influence of an opposing building façade obscuring part of the western sky vault and the solar disc. The obscured part is marked by azimuth interval [0; 60] and elevation interval [0; 45] (degrees). The diffuse reflectance is set to 0.3. The figure shows a maximum relative error of 30% in the back of the room and 10-20% in the rest of the room, but since the reflection algorithm is strongly simplified a certain discrepancy is expected. Buildings are almost always placed in a built environment, so further work is required to obtain satisfactory results for multiple reflections between building facades and the ground.

6. Conclusion

The tool described here is developed to evaluate the impact of incoming daylight on the energy consumption for lighting. The tool calculates the daylight distribution on the basis of a ray-tracing approach and the radiosity method to enhance accuracy while maintaining calculation speed.

The daylight distribution is calculated every hour, thus providing the information necessary for the thermal program to control the photoresponsive lighting and to calculate the heat load of the electrical lighting system. The daylight and thermal simulations are integrated meaning that the indoor temperature is recalculated if overheating or glare have caused the shading to be activated.

The daylight algorithms are validated by comparison with Radiance and they show good agreement for isotropic optical materials, and reasonable agreement for complex shading devices like blinds. The discrepancies are mainly due the fact that we use profile-angle dependent light transmittances for blinds because WIS data for the time being is uni-directional. However relative errors of 20% are considered satisfactory in the early stages of daylighting design where simulation speed and ease of use is of importance. Consequently the simplified tool is adequate for predicting the electrical energy consumption of photoresponsive lighting systems, including the impact of complex shading systems such as external Venetian blinds.

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Nomenclature

A	area, m^2
E	illuminance, lm m^{-2} (lux)
d	slat distance, m
dh	diffuse horizontal illuminance, lm m^{-2} (lux)
L	luminance, lm m^{-2} Sr^{-1}
lv	relative luminance
m	total number of subsurfaces
Mo	exitance, lm m^{-2} (lux)
w	slat width, m
α	azimuth, rad
β	slat angle, rad
γ	elevation, rad
η	luminous efficacy, lm W^{-1}
θ	profile angle, rad
ξ	angle of incidence, rad
ρ	reflectance
σ	visible proportion
τ	visual transmittance
χ	normalization factor
Φ	solid angle, Sr

Indices

build	opposing building
cut-off	angle that cuts off direct light
dir	direct light
dir→dif	diffused direct light
redir	redirected light
g	glazing
ground	ground vault
n	normal
sky	sky vault
sun	solar disc
v	vertical

Table 1 Data assumptions for validation. Radiance material properties in parentheses.

Room dimensions	Height x Width x Depth	3 m x 4 m x 6 m
Glazing	Height x Width	1.6 m x 2.0 m
	Offset	Symmetrical, 0.9 m from floor
	Type	Double glazing with lowE coating (4-15Ar-SN4)
	Light transmittance ⊥	0.782 (transmissivity = 0.852) (void glass glazing 0 0 3 .852 .852 .852)
	Overhang	Length: 0.4 m, 0.1 m above window, reflectance: 0 Not used for CIE overcast sky validation
Shading devices	Blinds WIS code: WinDat #01	slat width: 0.08 m, slat distance: 0.072 m slat thickness: 0.5 mm no curvature, no specular properties Diffuse reflectance: 0.096 (void plastic blinds 0 0 5 .096 .096 .096 0 0)
	Screen WIS code: Verosol SilverScreen	Light transmittance: 0.0354 (void trans screen 0 0 7 1 1 1 0 0 0.0354 0.82)
Diffuse reflectances	Walls	0.7 (void plastic walls 0 0 5 .7 .7 .7 0 0)
	Ceiling	0.8 (void plastic ceiling 0 0 5 .8 .8 .8 0 0)
	Floor	0.3 (void plastic floor 0 0 5 .3 .3 .3 0 0)
	Glazing	0.215 (cannot be specified)
	Albedo	0.2 (-g option to gensky)
Calculation settings	Subsurface size	0.5 m x 0.5 m
Measuring points	11 half meter interval points along centre line of room	
Sky model	Perez anisotropic sky	

Table 2 Input parameters to Radiance simulation.

Ambient bounces	Ambient division	Ambient sampling	Ambient accuracy	Ambient resolution	Direct threshold	Direct sampling
7	4096	2048	0.1	256	0.03	0.02
Mkillum options		-ab 4	-s 64	-d 96		

Figure 1 Room with window surrounded by sky hemisphere and ground hemisphere. Above the horizon the sky-model luminosity is applied, below the ground a constant luminosity is applied.

Figure 2 Illustration of how an incoming ray of light from the sky, sun or ground is transmitted directly, diffused in the combined glazing and shading system, or redirected specularly with equal angle of incidence and reflection.

Figure 3 Definition of illuminance and power density relationship for lighting systems in the BC/LC tool.

Figure 4 Illustration of the cut-off shading control strategy for adjustable slats. Sun is projected unto the plane perpendicular to the window plane.

Figure 5 Calculation procedure for the integrated daylight and thermal simulation.

Figure 6 Detailed daylight factor [%] distribution output from the BC/LC tool.

Figure 7 The artificial general lighting system complements the daylight to reach a user-specified set-point.

Figure 8 Dimensions of the validated room.

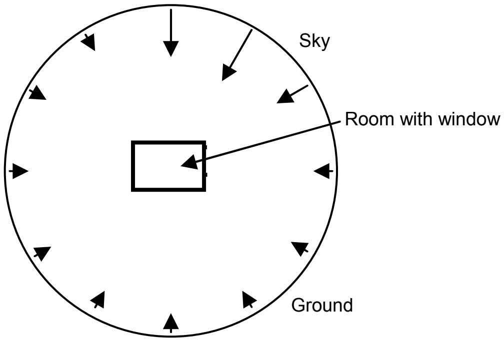
Figure 9 Comparison of case with daylight factors from CIE standard overcast sky model and a clear double glazing with low-E coating.

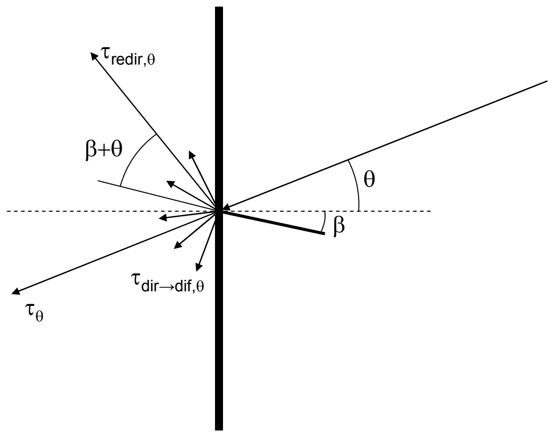
Figure 10 Comparison of case with clear double glazing and the Perez sky model.

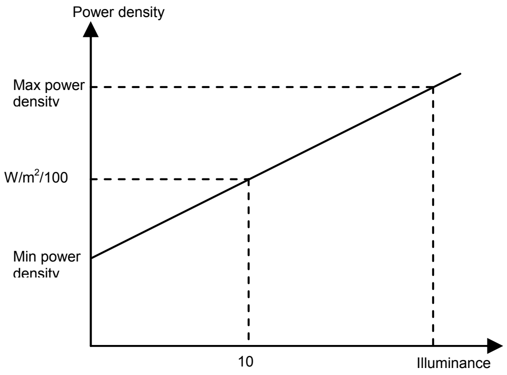
Figure 11 Comparison of case with screen lowered.

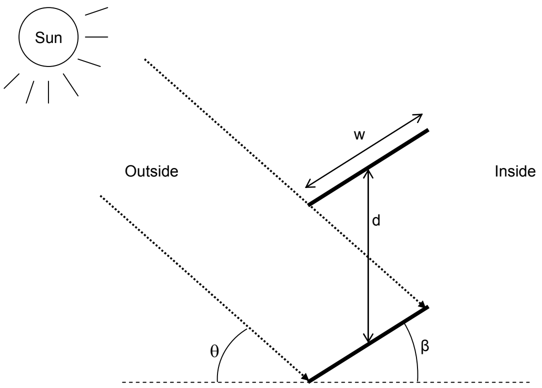
Figure 12 Comparison of case with blinds lowered and adjusted to cut-off angle.

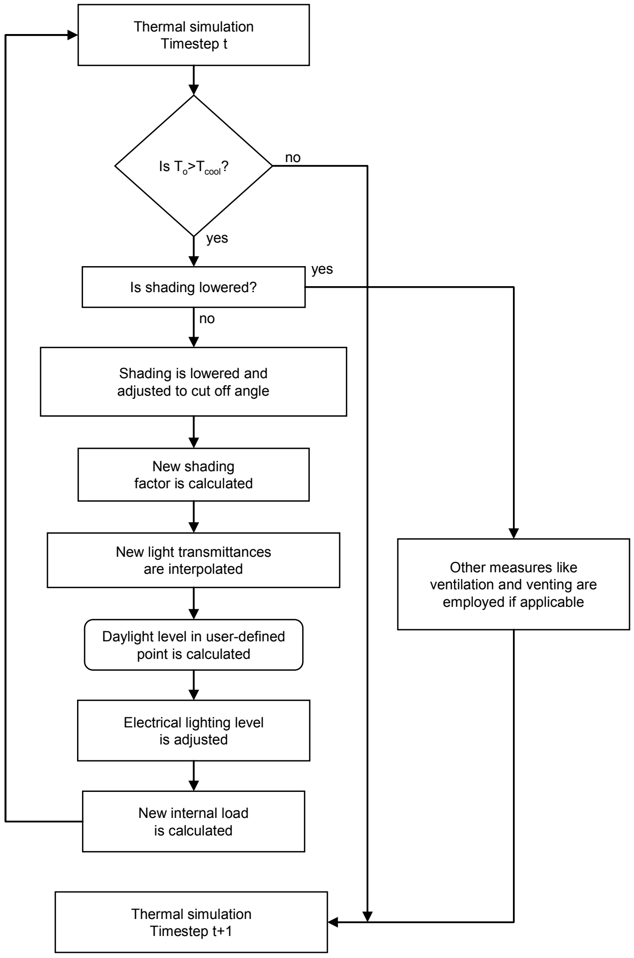
Figure 13 Comparison of case where opposing building obscures part of the sun and sky. Clear double low-E glazing.

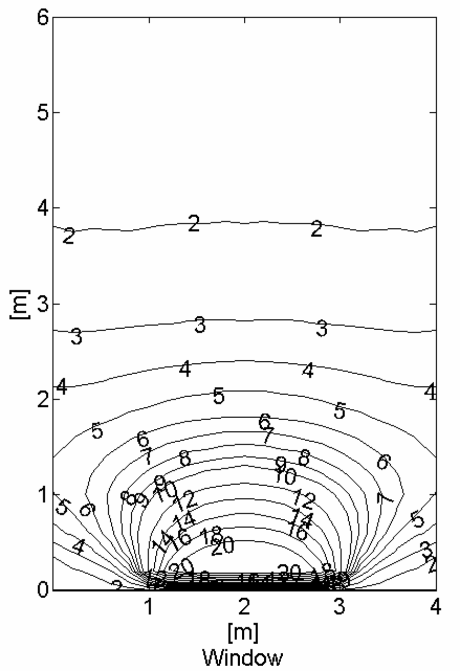

Sky
Room with window
Ground


$\tau_{redir,\theta}$
$\beta+\theta$
θ
β
$\tau_{dir\rightarrow dif,\theta}$
τ_{θ}

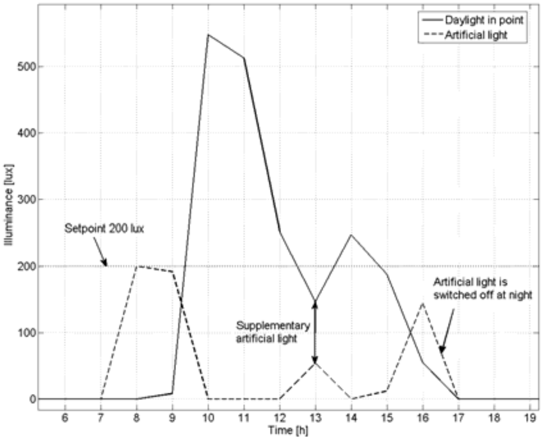

Power density
Max power density
W/m²/100
Min power density
10
Illuminance

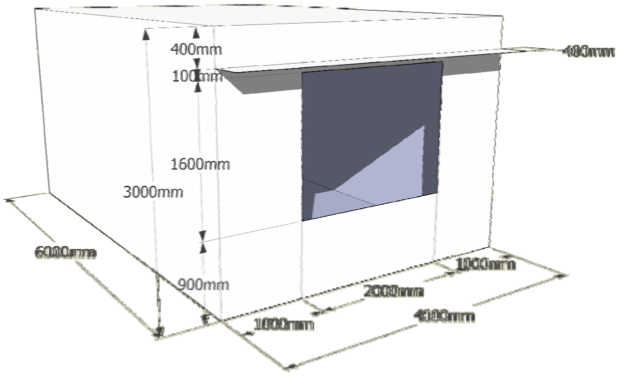

Sun
w
Outside
Inside
d
θ
β

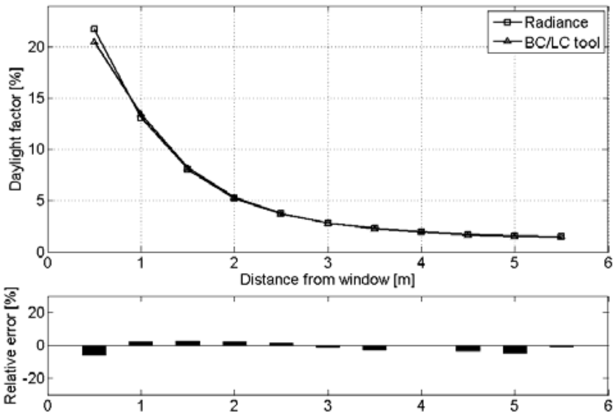

Thermal simulation
Timestep t
Is $T_o > T_{cool}$?
no
yes
Is shading lowered?
yes
no
Shading is lowered and adjusted to cut off angle
New shading factor is calculated
New light transmittances are interpolated
Daylight level in user-defined point is calculated
Electrical lighting level is adjusted
New internal load is calculated
Other measures like ventilation and venting are employed if applicable
Thermal simulation
Timestep t+1

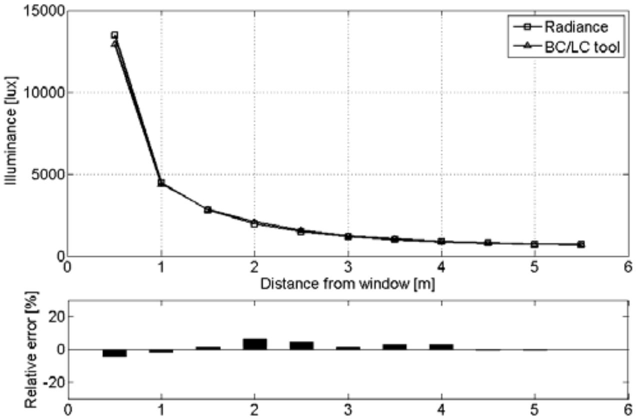


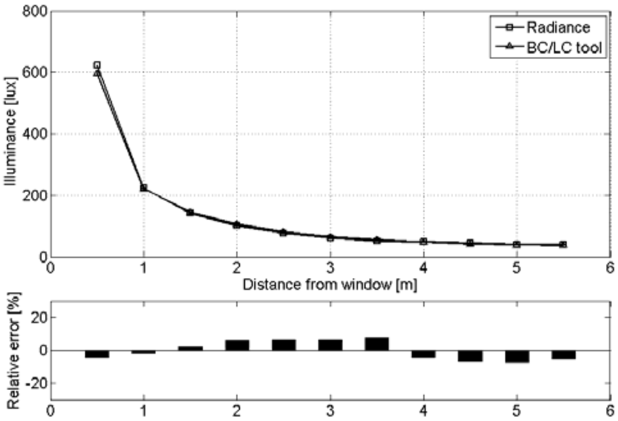
6
5
4
3
2
1
0
[m]
1
2
3
4
[m]
Window
2
3
4
5
6
7
8
9
10
12
14
16
18
20


Daylight in point
Artificial light
Illuminance [lux]
500
400
300
200
100
0
Setpoint 200 lux
Supplementary artificial light
Artificial light is switched off at night
6
7
8
9
10
11
12
13
14
15
16
17
18
19
Time [h]

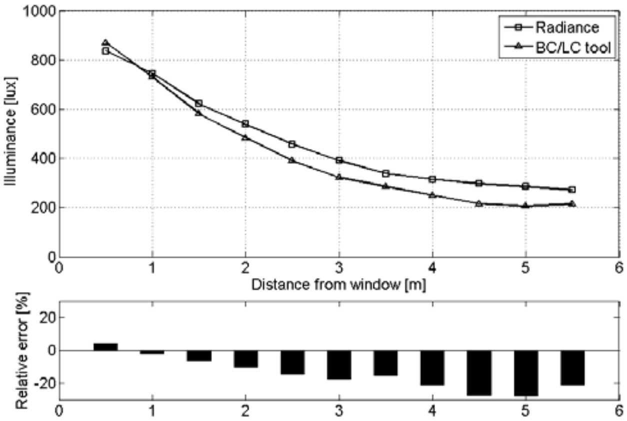

400mm
100mm
1600mm
3000mm
900mm
6000mm
400mm
1000mm
2000mm
1000mm
4000mm


Radiance
BC/LC tool
Daylight factor [%]
Distance from window [m]
Relative error [%]
0
5
10
15
20
20
0
-20
0
1
2
3
4
5
6

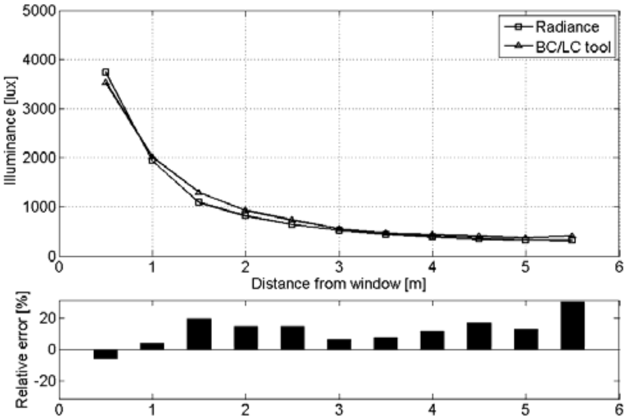

15000
10000
5000
0
Illuminance [lux]
Radiance
BC/LC tool
0
1
2
3
4
5
6
Distance from window [m]
Relative error [%]
20
0
-20
0
1
2
3
4
5
6



800
600
400
200
0
Illuminance [lux]
Radiance
BC/LC tool
0
1
2
3
4
5
6
Distance from window [m]
20
0
-20
Relative error [%]
0
1
2
3
4
5
6



1000
800
600
400
200
0
Illuminance [lux]
Radiance
BC/LC tool
0
1
2
3
4
5
6
Distance from window [m]
20
0
-20
Relative error [%]
0
1
2
3
4
5
6


Radiance
BC/LC tool
Illuminance [lux]
5000
4000
3000
2000
1000
0
Distance from window [m]
0
1
2
3
4
5
6
Relative error [%]
20
0
-20