Calculation of daylight distribution and utilization in rooms with solar shadings and light redirecting devices

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SUMMARY*:*
This paper presents a simplified method to evaluate daylight distribution in rooms with window systems utilizing solar shadings and light redirecting devices. The daylight calculation is useful to evaluate visual comfort, electric energy consumption for artificial lighting, and can be coupled to a simplified thermal model to evaluate the impact of daylight utilization on hourly temperatures, heating and cooling demands.

Calculation of the daylight distribution in a room is based on the radiosity method and all internal surfaces are assumed to be diffuse reflectors. The daylight transmitted through windows is split into three parts: diffuse light, direct transmitted light, and redirected transmitted light. The surfaces in the room are divided into smaller rectangular elements and the radiosity method is applied to calculate illumination on each element based on their initial luminous exitance. The direct transmitted light and the redirected transmitted light are distributed on the rectangular elements based on the sun path of direct and redirected light. The elements which are hit by direct or redirected light are treated as light sources with luminous exitance based on the amount of direct and redirected light on the element.

The objective of the method is to enable coupled evaluation of daylight, artificial lighting, energy consumption for heating and cooling in the early design phase based on a limited amount of information on the building design. The chosen approach enables a simplified hourly evaluation of the daylight utilization with fast calculation speed and reasonable accuracy.

1. Introduction

Daylight is important for conception of the visual environment and better utilization of daylight may reduce the need for artificial lighting and internal gains caused by solar energy and electric lighting. Daylight may cause problems with glare on workplaces or other places in the visual environment. Solar shadings are often applied to control glare and to reduce solar gains in order to avoid over heating. Often too much daylight close to the windows results in activation of solar shadings and artificial light will be needed in locations further from the windows. To solve this problem solar shading with light redirecting properties can be applied. The objective of the light redirecting device is to reflect sunlight toward the ceiling of the room which creates a more uniform level of daylight throughout the room. The light redirecting device should still function as a solar shading to avoid glare problems close to the window and reduce solar gains.

The indoor climate is an important factor for productivity. Good indoor climate increases the productivity of the employees working in the building (Heschong et al., 2003). People are spending more time working on computers and people want to work in the zone closest to the windows to maintain a view out

(Christoffersen et al, 1999). Glare problems, such as reflections from monitors, are therefore a relevant issue and the risk of glare increases with larger glazing area and it is essential to provide good quality lighting through transparent systems of the building.

Simple methods to evaluate daylight are based on overcast skies and are useful to evaluate the minimum availability of daylight. These methods do not take into account the direct sunlight and position of the sun and cannot give information on glare problems or light distribution in rooms in cases with direct sun light. Detailed methods based on ray-tracing calculate detailed distribution of daylight and produce photo realistic images of the daylight distribution in the room at a given time. These methods require substantial input data and calculation time. Therefore, ray-tracing methods are not appropriate for hourly simulation of the daylight conditions. Several simplified methods to evaluate daylight distribution including effects of direct sunlight exist. Often these methods are only developed to evaluate unobstructed transparent systems. They greatly simplify effects of solar shadings and do not take light redirecting devices into account.

It is not easy to select the optimal window system that gives the building the best balance between solar energy transmission and transmission of daylight. Several calculation methods have been developed to guide engineers and architects to choose a right solution of window system that result in good indoor climate and low energy consumption. Yet simple calculation tools that take into account some of the more complex properties of window systems are not available. This paper describes a simple method to calculate daylight distribution in rooms with solar shadings and solar redirecting devices. The method is still under development but has the potential of becoming a useful tool in the early design phase to guide building designers toward window systems that ensure good indoor climate and low energy consumption.

2. Methods to calculate daylight distribution

Several methods and tools to determine daylight distribution exist. Methods vary from simple factor calculation method to complex algorithm methods such as ray-tracing. The developed method uses the radiosity method which has a reasonable balance between the calculation time and accuracy. Some of the existing methods and programs are mentioned below.

2.1 Factor methods

One of the most used methods is the daylight-factor method which is often limited to cases of an overcast sky. The daylight-factor is calculated by using nomograms and the best known daylight factor method is the BRS daylight Proctator. The daylight-factor is the relation between the illuminance on an indoor surface and the exterior horizontal illuminance. An improved factor method is the solar-factor method that has been developed by the Danish Building Research Institute. This method use solar-factors given as the illuminance on the surface inside the room divided by illuminance on the exterior of the window (Christoffersen et al., 1999). These factor methods show good indication of how much daylight enters the building for simple sky conditions with standard unobstructed window systems.

2.2 Ray tracing methods

A high resolution rendered picture of an object or a plane from a viewer’s eye can be generated using the ray tracing method. With computer algorithms and processor power, millions of light rays can be traced from a given object to the light source which is usually the sun position (backwards ray tracing).

The program Radiance uses this ray tracing technique (Ruck et al., 2000). Radiance can use an interface of a CAD program and with a detailed drawing of a building Radiance can simulate a realistic picture inside the model from a given view. This method is accurate and illustrates the daylight distribution in buildings. But the method requires detailed input and the simulation time is long for only one situation.

2.3 Radiosity methods

Another method often used in computer simulation program is the radiosity method. The method is developed from thermal radiation exchange theory which is used to determine the thermal radiation exchange between surfaces. The radiosity method has a significant advantage over the daylight factor method because it allows inter-reflections between surface walls. The method is not as accurate as the ray-tracing method but the calculation time is shorter. The surfaces are assumed to be perfect diffusers that reflect equally amount of light to all directions (Lambert's law). By defining the window as a light source the daylight distribution in a room can be calculated from the inter-reflections between surfaces defining the architectural space. Parasol and Lightscape are simulation programs that use this method (Bülow-Hübe, 2001).

3. Simple method for calculation of daylight distribution

A simplified calculation method is developed based on the principles of the radiosity method. The radiosity method is used on the basis that it has shown good results, is simple, the calculation time is fast and fairly accurate (Park and Athienitis, 2003), (Bülow-Hübe, 2001). The developed method uses visual transmittances as input and the exterior illumance on the window and solar position is computed with solar algorithms.

To calculate how much sunlight is transmitted through the window system it is necessary to evaluate the visible transmittance and the amount of sunlight on the exterior of the window system. Visual transmittance of a transparent system can be calculated according to the standard ISO 15099 (ISO, 2001) for both direct and diffuse sunlight. Solar algorithms based on weather data are used to calculate how the amount of sunlight on surfaces that represent window systems. To evaluate the energy balance the total energy transmittance (g-value) gives the amount of solar energy transmitted through the window system.

Currently the method is limited to calculate daylight distribution in simple box shaped room with one rectangular window. The wall surfaces are divided into an arbitrary number of elements (subsurfaces) that are characterised by their light reflectance. The reflectance of each surface is assumed to be diffuse and view factors from one subsurface to surrounding subsurfaces in the room are calculated based on geometrical relations between surfaces.

The surface representing the window and subsurfaces in room lit by direct or redirected sunlight are treated as initial diffuse light sources. The exterior illuminance on the transparent system (E_{tot}), the visual transmittances (τ_{tot}) and position of the sun are needed to calculate the initial luminous exitance (source) of the surface representing the window. The illuminance of diffuse light from the sky (E_{dif}), direct light (E_{dir}) and reflected diffuse light (E_{dif_ref}) on the exterior of the window, are calculated based on Perez solar algorithms (Perez et al., 1990). Fig 1 shows the situation and the total light transmitted per area of the window is given by

$$E_{t\_tot} = E_{tot} \cdot \tau_{tot} = E_{dif} \cdot \tau_{dif} + E_{dir} \cdot \tau_{dir} + E_{dif\_ref} \cdot \tau_{dif\_ref} \quad (1)$$

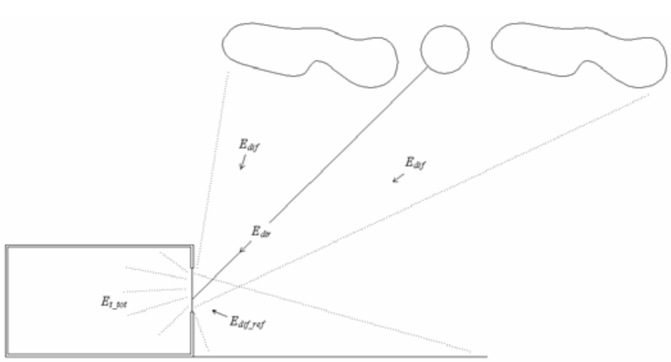

FIG. 1: The total light transmitted E_{t_tot} is found with the visual transmittance and the illuminance on window from diffuse, reflected and direct sunlight.

The direct light on the exterior of the window system may be reflected and diffused by components in the window system. The method assumes that a part of the direct light is transmitted as diffuse or redirected light with a given direction determined by the components in the window system. The direct visual transmittance (τ_{dir}) gives the total fraction of the direct light transmitted to the room and is split into three parts: one part that is transmitted as diffuse light (τ_{dir_dif}), one part that is transmitted with the direction to the sun (τ_{dir_dir}), and one part that is redirected with a known direction (τ_{dir_redir}).

$$\tau_{dir} = \tau_{dir\_dif} + \tau_{dir\_dir} + \tau_{dir\_redir} \tag{2}$$

The visual transmittances above can be calculated with the program WIS (Window Information System) except for the redirected light (τ_{dir_redir}). WIS uses the standard ISO15099 to calculate transmittances (van Dijk and Kenny, 1996).

The direct and redirected light transmitted through the transparent system from the sun is distributed on the subsurfaces hit by the direct and redirected light. View angles ($\gamma_{1\text{-}4}$ and $\alpha_{1\text{-}4}$) from the center of each subsurface to the window or shadow edges are found. For direct transmitted sunlight a subsurface inside the room is assumed hit by direct light if the vertical shadow angle (γ_5) and horizontal shadow angle (α_5) of the sun are within the maximum and minimum of the view angles. The same test is made for the direction of the redirected light. Fig. 2 illustrates the situation.

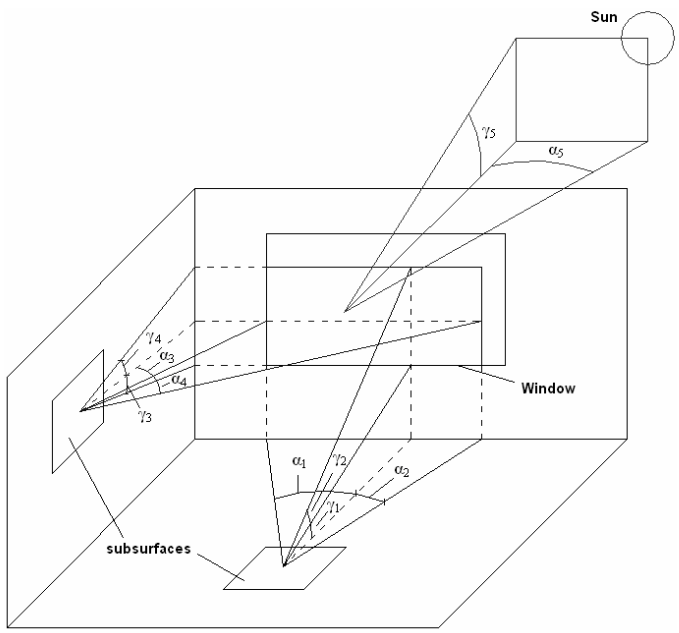

FIG. 2: A subsurface in a room is hit by direct sunlight if sun altitude (γ_s) and azimuth (α_s) are within the view angles from the middle of the subsurface to window or shadow edges.

The intensity of light on a given surface depends on cosine of the incidence angle of the direct light on the surface. In order to have the right balance between the direct light transmitted through the window system and the sum of light on the subsurfaces, the intensity of direct light on the subsurfaces is weighed related to the total amount of direct transmitted light. The intensity E_{i_dir} of light on each surface hit by direct light is given by

$$E_{i\_dir} = E_{t\_dir} \cdot A_g \cdot \frac{A_i \cdot \cos\theta_i}{\sum_{j=1}^{n} A_j \cdot \cos\theta_j} \tag{3}$$

with amount of transmitted direct light per area of window system E_{t_dir} , area of the glazing A_g , the incidence angle θ and number of surfaces hit by direct sunlight n.

When the final luminous exitances of surfaces that represent the light sources are known, the radiosity method is used to calculate illuminance on all surfaces of the room model. This distribution is then used to calculate illuminance on fictive horizontal or vertical planes and in given points.

Fig. 3 shows the illuminance calculated with the developed method on a fictive plane in the 85 cm above the floor. The left window illustrates the position of the plane and the right window illustrates the same plane with more accurate calculation. The bar scale has the unit *lux* and indicates the illuminance level on the fictive surface.

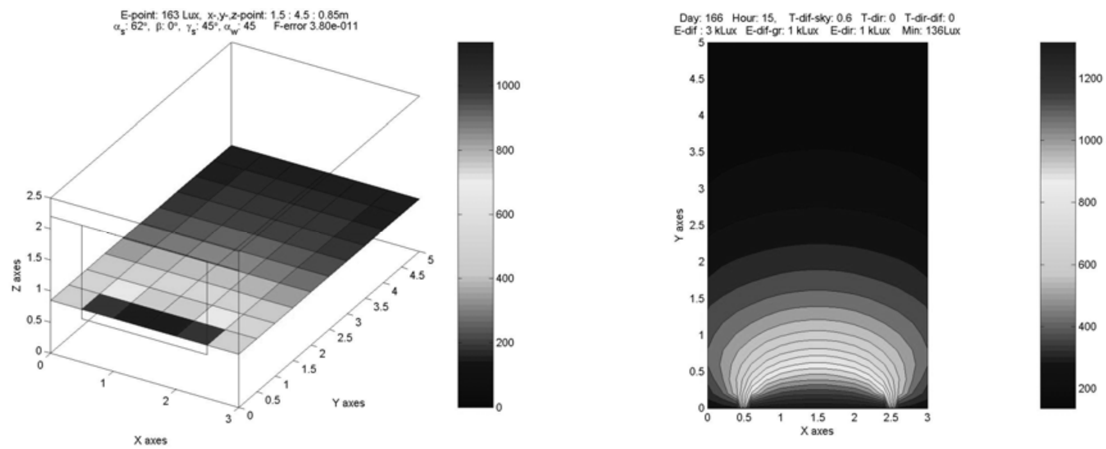

FIG. 3: Calculated results with developed method. The left window illustrates the position of the fictive horizontal plane showing the illuminance of each subsurface. The right window illustrates the same fictive plane with more accurate calculation.

The influence of the redirected direct light from solar shading device can be calculated if the visual transmittance (τ_{dir_redir}) and direction of redirected direct light are known. This is relevant to include if a solar shading device reflects significant amount of sunlight into the back of the room. The current method calculates the direction of redirected light based a mirrored beam from a venetian blind without inter reflections between slats. Fig. 4 shows the ceiling of a room where redirected light is reflected onto the ceiling from solar shading device.

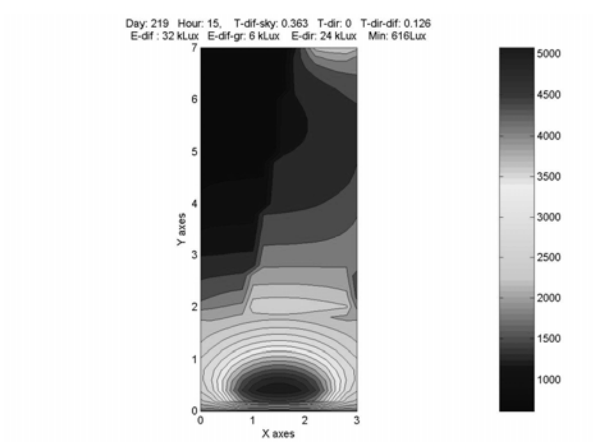

FIG. 4: Case with redirected sunlight reflected onto the ceiling. The reflected light increases the illuminance in the back of the room

4. Validation

Daylight factors calculated with the developed method are compared with daylight factors from a real scale model and daylight factors from two other simulation tools, Radiance and Parasol. Comparisons are made for a simple box shaped room with a standard window (visual transmittance of 0.8), for an overcast sky, with and without a solar shading device. Fig. 5 shows the calculated and measured daylight-factors as a function of the distance from window.

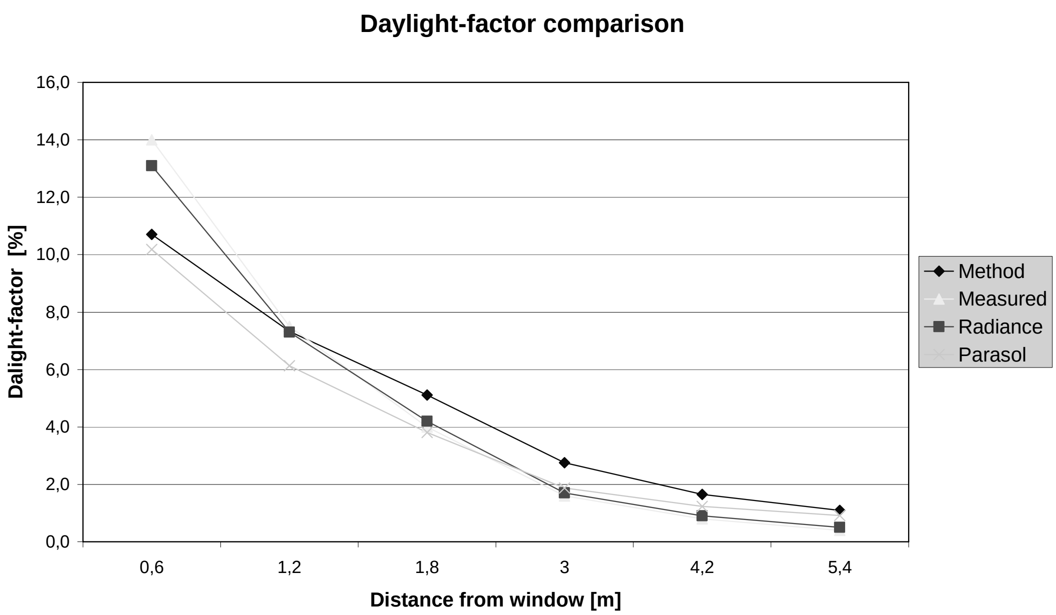

FIG. 5: Daylight-factors calculated by the presented method compared with measured daylight factors and daylight factors calculated with other simulation programs.

With no solar shading device, the developed method slightly overestimates the illuminance level in the back of the room (far from window), and underestimates the illuminance level close to the window. The window is simplified in the developed method to act as a lambertian diffuse surface distributing the diffuse light from the sky and the ground equally in all directions. In reality the diffuse light transmitted through window is not distributed evenly. The lower part of the room receives a larger part of diffuse sunlight because it is more exposed to the sky.

With a solar shading device (venetian blind) attached to the window, the actual distribution of the diffuse sunlight from window is more equally distributed in all directions due to reflections and inter-reflections between slats. Fig. 6 show calculated and measured daylight factors as a function of distance from window.

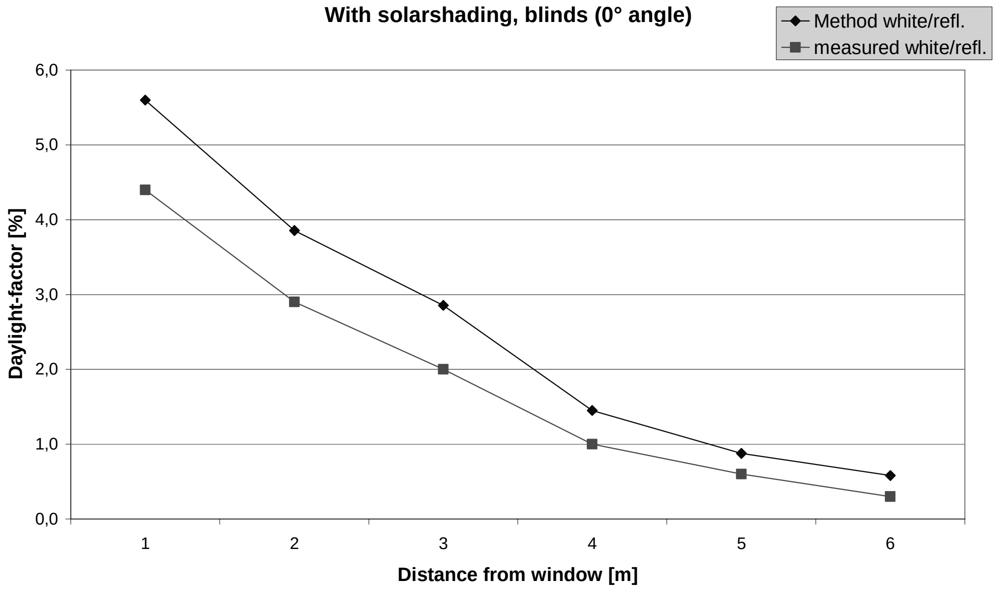

FIG. 6: Daylight-factors from method compared with daylight-factors from measurement. With solar shading device (blinds).

The daylight distribution calculated with the presented method follow the measured values at a higher level. In the shown case, the visible transmittance of the transparent system used in the measurements is estimated from the product used in the experiment. The results indicate that the visual transmittance used in the calculations is slightly higher than in the measured.

Overall the presented method shows good agreements with results from measurements and other simulation tools. The method has the advantage over detailed simulation programs, which use the ray-tracing method, that it has a short simulation time but can simulate with equally complex window systems.

The method is useful for dynamic calculation returning hourly illuminance values for a certain point or surface in the room. With these values the use of electric energy for artificial lighting can be estimated. The method can be coupled to a simplified thermal model to evaluate hourly temperatures, heating and cooling demands.

In cases with unobstructed window systems the daylight levels calculated far from the window are too optimistic. To improve the distribution of diffuse daylight in room view factors to the sky and ground should be calculated separately. In cases with solar shadings the method shows better results because much of the light from the exterior is transmitted as diffuse light due to inter reflections in the solar shading.

5. Conclusions

This paper presents a method to evaluate daylight distribution in cases with solar shadings and light redirecting devices. The method is based on the radiosity method to calculate light distribution in a box shaped room with one rectangular window. The direct sunlight is split into three parts: one part that is transmitted as diffuse light, one part that is transmitted with the direction to the sun, and one part that is redirected with a known direction. The direct and redirected light is distributed on the internal surfaces based on the direction of the direct and redirected light.

Results calculated by the presented method are compared to measured values and values calculated by two other tools. The results shows that in cases with a clear unobstructed transparent system the presented method overestimates the illuminance level far from window and underestimates the illuminance level close to the window. This is a result of the simplification that the diffuse light on the exterior of the window is distributed evenly in all directions into the room. In reality the luminance of the sky is higher than the luminance of the ground. Therefore, the lower part of the room receives a larger part of the diffuse sunlight.

In cases with solar shadings the presented method gives better results because much of the light from the exterior is transformed into diffuse light due to inter reflections in the solar shading.

The simplicity of the presented method makes it useful for dynamic calculation of hourly illuminance levels for certain points in the room. These values may be used to control artificial lighting and thereby estimate savings in electric energy. Also these results may be coupled to a simplified thermal model to evaluate the impact of the daylight control on hourly temperatures, heating and cooling demands.

In general the method shows promising results but needs to be improved for cases with clear unobstructed transparent systems.

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