# DAYLIGHT MODELLING WITH PASSPORT-LIGHT

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**ABSTRACT**

This paper describes the use of daylight coefficients in a computer tool which is based in Monte Carlo backward ray tracing merthod and was developed under the frame of DAYLIGHT- Europe EC Project. Following the daylight coefficients approach the intereflection calculation is carried out once for each zone and it doesn't have to be repeated if the sky luminance distribution changes. It is obvious that the advantage of the approach is that hour by hour calculations of interior lighting in a building for a whole year can be performed fast without the repetition of the intereflection calculation even if the building contains innovative daylighting systems like mirrored lightselves or prismatic glazing.

**INTRODUCTION**

During the design stage of a building one of the considerations taken into account is the evaluation of the luminous environment. Predictions of daylighting levels are, by necessity, subject to a compromise between accuracy and numerical complexity.

Although there are a lot of computer programs for the determination of the illumination due to a specific layout of luminaires distribution, there are only a few programs that take into account the effects of daylighting [ Bellia et al., 1994].

There are two approaches which can be used for the detailed estimation of the luminouw environment in the interior of a building. The first is radiosity [ Goral et al.,1984] while the second is ray-tracing. Both are capable of producing numerical results and high-quality pictures as well.

In the radiosity method a given space is divided into a mesh of patches. Each patch is considered as a Lambertian reflector, which means that it has a constant luminance, independed of the viewing direction. The flux that leaves each patch is given by the Lambert's cosine law. Therefore, each patch receives and reflects light back into space. The whole process is iterative and proceeds until all the reflected flux has finally been absorbed. The calculation of view factors between different patches is one of the most difficult parts of this method . As view factors have to be stored, the amount of data storage required increases as a function of the number of patches. It is evident that this method cannot model specular reflection effectively. Different models have been developed using the radiosity method. One of these tools is Superlite [Hotchcock R. and Osterhaus W., 1993]. This tool was originally developed during 1985 using the radiosity method for the calculation of daylighting levels on any given plane in the interior of a building. Although it can support complex geometry, there is a limitation on the number of surfaces, (maximum 30 in ver.2). This tool can model uniform, standard CIE overcast sky and CIE clear sky with or without sun. There is no integration between interior daylight levels and a corresponding electric lighting system dimming response and a separate software link should be used. One of the disadvantages as mentioned before is that specular reflecting surfaces cannot be simulated. Therefore the influence of shading devices like venetian blinds, light shelves, mirrors, in the energy consumption due to electic lighting cannot be estimated.

Ray-tracing techiques can easily deal, with complex building forms more simply. Rays are emmitted from the light source (forward ray-tracing) striking surfaces in space, contributing to the luminances of these surfaces. An inverse process can be used in which the rays are emitted from a point in the scene trying to trace the light sources (backward ray-tracing). Each ray carries a "weight" which is proportional to the intensity of the corresponding ray. After an intersection with a surface, new rays are generated and their weight depends on the reflection. When the weight of one ray falls below an arbitary value, it is taken to be absorbed and the process is repeated with a new emission.

The emission of the rays to different directions is time consuming and demands large proceccing time. To reduce the processing time, ray-tracing is often combined with a statistical method of calculating the ray emission, (Monte Carlo). Ray-tracing techniques excel in the rendition of point light sources, specular reflections and refraction effects.

A well known tool based on ray-tracing technique is Radiance [Ward G., 1994] . This tool is a physically based rendering program. It uses a light-backward ray tracing method that is capable of solving the rendering equation [Kaliya J., 1984] under any kind of reflection and transmission, in any environment including complicated curved geometry. For the simulation, deterministic and stochastic ray-tracing techniques are used to achieve the best balance between speed and accuracy. Color visual representation of the space is possible and most important with calculated luminance values. Although Radiance is capable of calculating light levels due to electric lights , there is no connection between the energy consumption due to electric lights and the daylight availability. This is due to the long processing time that each calculation demands. Hour to hour simulation , although possible, is not recommended because of the dramatically long processing time.

Concerning the visualization of the results, ray tracing is a view-depended process. This means that when the view position is changed, a large part of the process has to be repeated. Radiosity is the exact opposite. Calculations are based only on the geometry of the environment.

There are five closely related objectives in estimating daylighting levels with the methods described above. The first is accuracy of the results. The second is the estimation of the impact of innovative daylighting devices. The third is the connection of the results to a building thermal simulation tool, the fourth is the reduction of the processing time and the fifth is the production of images.

Tools based on radiosity have a problem on using innovative daylighting devices since they can’t model surfaces with specular reflection or surfaces as prismatic glazing.

On the other hand ray-tracing based tools can offer accurate results in most cases [Mardalijevic et al., 1995]. Due to greater processing time these tools cannot be used in conjunction with an energy analysis program. Passport - Light uses the daylight coefficient concept to fill the gap between the existing lighting design tools. With this method the impact of innovative daylighting devices can be easily estimated since the time consuming part of the calculation procedure doesn’t have to be repeated.

## DESCRIPTION OF THE METHOD

Daylight coefficient [Tregenza P., 1983] is defined as the ratio between the luminance of a patch of sky and the illuminance in the building due to light from that patch :

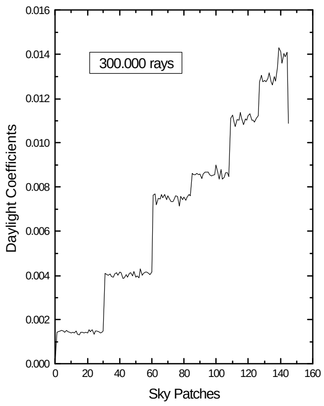
$$d_k = \frac{E_k}{L_k\ a_k} \qquad (1)$$

where $L_k$ is the luminance of the sky patch, $E_k$ is the illuminance at a point in the room and $a_k$ is the angular size (solid angle ) subtended by the sky patch.

The sky can be divided into zones of altitude and azimuth and the daylight coefficient found for each zone. Total illuminance at one point in a room can then be calculated using the equation:

$$\text{Illuminance} = \sum_{k=1}^{\text{number of sky patches}} L_k\ a_k\ d_k \qquad (2)$$

where $L_k$ is sky luminance,$a_k$ is the subtended size of a sky patch and $d_k$ is the daylight coefficient. Following the daylight coefficients approach the intereflection calculation is carried out once for each zone and it doesn’t have to be repeated if the sky luminance distribution changes. It is obvious that the advantadge of this approach is that hour by hour calculations of interior lighting in a building for a whole year can be performed fast without the repetition of the intereflection calculation. Additionally , because the sky is treated as a number of point sources, the contribution of direct and reflected sunlight in the interior lighting could easily be assesed by adding, in the sky zone where the sun is located, an additional luminance equal to the normal solar illuminance divided by the solid angle of the zone. The resulting imprecision is the blurring of shadow edges and an error up to seven degrees in the position of the sun center. Such a degree of accuracy is satisfactory in general illuminance calculations. To calculate daylight coefficients [Littlefair P., 1992], Passport-Light uses the Monte-Carlo approach [Tregenza P., 1984], a

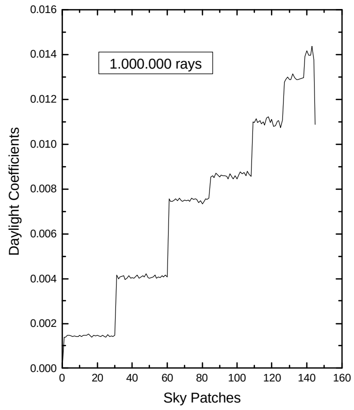



kind of backward raytracing. Rays are emitted from the reference plane in directions that are samples
from the probability distribution that model the physical principles of the behavior of light. The zenith angle and the azimuth of the emitted rays are given by the following formulas [Siegel R. and Howell J., 1992]:

$$Azimuth = 2 \cdot \pi \cdot R_1 \qquad (3)$$

$$Zenith = \sqrt{R_2} \qquad (4)$$

where $R_1$ and $R_2$ are random numbers.
Each emitted ray has an initial weight equal to 1. After each reflection or transmission the ray weight is multiplied by the corresponding reflectance or transmittance of the surface. The rays are recursively tracked through reflections and transmissions and if their weight is greater than a predefined limit ray-weight, it is accounted by the sky patch corresponding to the specific direction. The ratio between the sky patch score and the total number of emitted rays determines the daylight coefficient. If the ray weight is lower than the above mentioned limit value the ray is considered to be absorbed.
The program can deal with a variety of reflection models. Particularly,the method considers specular, diffuse reflective and diffusing glass. The model considers the ground as a aeparate surface. For all rays that do intersect with the ground a single ground reflected daylight coefficient is calculated.
Although the above mentioned process can be used for the calculation of illumination, it is preferable to separate the calculation in two main parts. The first part will calculate the direct component (i.e. illumination from the sky) while the second part will be responsible




for the intereflections. This reason for such a separation can be shown in figure 2.

Fig. 2. Figures showing the estimation of daylight coefficients against number of rays.

Figure 2 presents the values of 145 daylight coefficients against a number of emitted rays, for a simple scene (horizontal surface, one point). It can be concluded that even for a such simple scene the calculation of illuminance could be performed using an extremely large amount of rays and hence the processing time increases dramatically. Each step of the above presented figures represents one sky band; for example the first band has an elevation of 60 and consists of 30 patches. The total number of bands is eight.
The above mentioned calculation could be performed by sending only 145 rays, one to each sky patch [CIE, Guide to recommended practice of daylight measurement, 1989], in order to estimate direct illuminance since intereflection doesn’t play any role.

**SIMULATION PROCEDURE.**
The first step of the calculation is to define the geometry of the space and the points where the calculation has to be performed. For each one of the points defined, a set of 145 daylight coefficients is calculated.
The process is then quite straightforward as described in the previous paragraph. Whenever a ray hits a surface a new ray must be emitted from the same location to ensure no accumulation of energy.
It is obvious that this calculation does not depend on sky luminance distribution.
The ratio between the mean reflectance of the space and limit ray-weight represents the average bounces of light.
Due to the statistical nature of the method, a fluctuation in the values of daylight coefficients is observed during the calculation procedure (fig. 2). This fluctuation is reduced by increasing the number of emitted rays and can cause errors in the calculation of

illuminance if the number of rays is unsufficient. For the same number of emmitted rays and the same geometrical scene, the error in the estimation of illuminance is smaller under uniform or overcast sky than clear one. This is because uniform or overcast skies show an azimuthal isotropy in luminance diastribution.

To overcome this situation the user has to use an extremely large amount of rays. Thus the processing time increases.

Comparison of the results to Superlite and Radiance has been performed using a rectangular room with dimensions of 5m x2.67m x2.67m was used as a test room. This room has one vertical opening of 2.6m x1.8m at 0.8m covered with clear glass facing south. The reflectance of the floor is 0.2 and of the ceiling and walls 0.6. An horizontal surface at 0.8 m has been taken as a reference plane. Three points across the length of the room were used as points where the calculation of illuminance will be made. The initial parameters that were used for the simulation with this method were 150000 initial rays and 0.01 for the ray-weight limit.

The calculation procedure was repeated for three different sky conditions.

a. Overcast conditions with Lz=5647 cd/$m^2$

b. Clear sky conditions with Lz=3335 cd/$m^2$ ,elevation $40.8^0$ and azimuth $41.3^0$ without sun.

c. Uniform sky conditions with Lz= 3062 cd/$m^2$.

The obtained results are givn in figures 4,5,6.

The results are presented in the figures below.

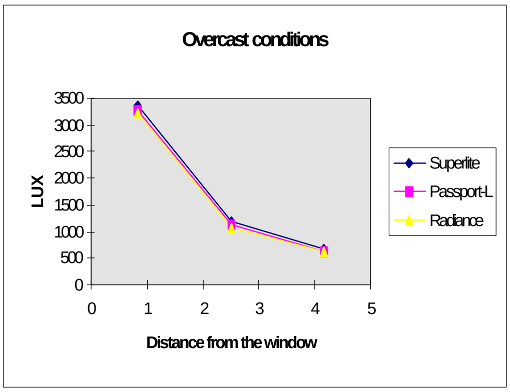



Fig. 3. Comparison of results under overcast conditions.

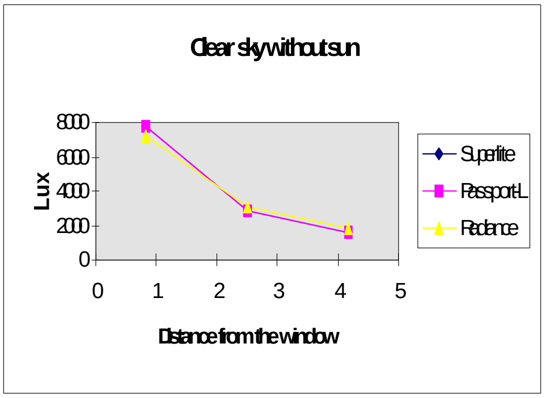



Fig. 4. Comparison of results under clear sky .

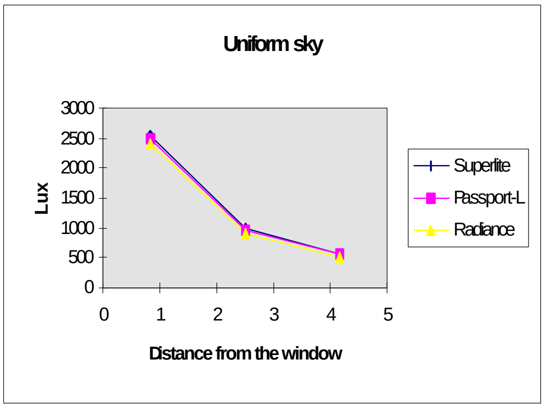



Fig. 5. Comparison of results under uniform sky.

Furthermore comparisons with real measurements show good agreement between predicted and measured illuminance values [Tsangrassoulis et al., 1996]. The use of large amount of emitted rays and low limit ray-weight causes an increase in processing time.

Separation of the calculation greatly reduces the problem.

Passport-Light divides the calculation in three parts:

- Direct
- Specular
- Interreflection

This separation as mentioned above is necessary for time economy since the direct calculation part is pure geometric. Each sky patch is divided in 144 subpatches. As a result 144 rays are emitted from each calculation point for each sky patch (thus the total number of rays that emmitted to estimate the direct component of illuminance is 20880) . This seems to be more time consuming but it is necessary if the user wants to calculate the direct component in a building with small windows or the calculation point is far away from the windows or the window has a shading device like venetian blinds.

The calculation procedure consists of the following steps:

1. Check for diffuse windows.
2. If there are diffuse windows, calculation of illuminance on the window is performed. In these windows the luminance is considered as constant.
3. Calculation of direct component.
4. Check if there are mirrors in the scene.
5. If there are mirrors, rays are emitted trying to evaluate the illuminance caused by the reflection of the sky on them (specular component).
6. Intereflection calculation is performed.
7. Results.

Four parameters set the calculation procedure.

1. Number of initial rays

The first parameter of the model is the number of initial rays. One of the problems of this program is the estimation of this number. Naturally the error in the estimation of illuminance is inversely proportional to the total number of rays. Since the error in the estimation of illuminance by an instrument is less than 10 % such an accuracy is desirable for the results. Thus, there is a compromise between the number of rays emitted (i.e. the simulation time) and accuracy.

During the calculation of intereflections a diagram is presented on the screen:

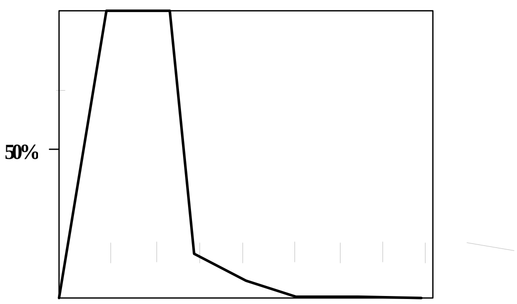



Fig.6. Vertical axis: Relative error in the estimation of illuminance

Horizontal axis : Percentage of the rays emitted

The horizontal axis has 10 subdivisions each representing 10% of the rays emitted . The vertical axis represents the relative error in value. The relative error must be lower than 10 %. Since the relative error is the relative error of illuminance and not the relative error of daylight coefficients it depends on sky luminance distribution. Such an approach means that skies with large luminance anisotropy (clear sky) have to be traced using a larger number of rays, while in an overcast or uniform sky, the number of rays is smaller. If the results will be used for a repetitive estimation of illuminance under different sky conditions, the first run must be performed using clear sky.

2. Limit ray-weight

The limit ray-weight is the second parameter which affects the results. This sets the “depth” of the interreflection. The upper value is 1 which -if used- in most cases will give results (due to interreflections) equal to 0. The value of this parameter must be lower than the transmittance of the glazing material because if the opposite happens then when a ray intersects a window, it will have a ray-weight less than the ray-weight limit and therefore the intereflection component will be zero, again.

The lower value of limit ray-weight is of course 0. This leads to an infinite calculation, which is not desirable. As mentioned above the ratio between the average reflectance of the space and the limit ray-weight is the average number of light bounces. Decreasing the limit ray-weight, the average number of light bounces are increased causing an increase in the values of daylight coefficients and an increase in processing time. According to relation (2) estimated illuminance is also increased. The following figure shows an example of the increase of calculated level of illuminance in a point which is located in the interior of a rectangular room, when limit ray-weight decreases.

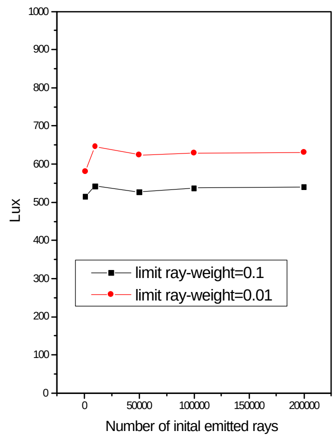



Fig. 7. Influence of the ray-weight limit to illuminance values

The value of limit ray-weight is defined by the user at the beginning of the calculation

3. Number of rays used for specular calculation
Passport-light can deal with specular surfaces (mirrors). If there are such material in the scene after the direct component calculation a number of rays is emitted in order to trace the mirrors. In this part of the calculation the rays under consideration, are these which follow the trajectory:

point-mirror-> window-> sky

excluding any kind of interference with the rest of the surfaces in the scene from the calculation.
During this calculation a diagram is displayed on the screen, showing the evolution of the relative error in the estimation of illuminance due to "virtual" sky . The word virtual means the image of the sky on the mirror.
A crude way for the estimation of this number is to divide the solid angle of the mirror as seen by the calculation point with the solid angle of the hemisphere.
It is possible to use a system with mirrors. The ray-weight limit is the same as above. Mirror enclosures must be avoided due to the extremely large calculation time.

4. Number of rays used for diffusing windows
Diffusing windows are considered to have the same luminance over their surfaces. For each diffusing window a number of rays are emitted in order to calculate the illuminance on the window. Then using the transmittance of the material this illuminance is converted to luminance. Since the external scene is quite simpler the number of rays is less than the initial number .

CONCLUSIONS
Artificial lighting can be a major energy consumer in some buildings. Thus the estimation of energy savings due to the use of daylight for a specific time period is essential. The choice of a lighting model for use in a dynamic thermal evaluation tool is a compromise between accuracy and computational expense. Radiosity based models have problems with the treatment of specular surfaces and transparent materials. On the other hand ray tracing models offer accurate results in most cases but due to greater processing time these models cannot practically be used in conjunction with an energy analysis program. Using Passport-Light in a preprocessing mode to calculate daylight coefficients representing point illuminances, offer benefits in terms of intergration with the energy analysis program, accuracy of the results even if innovative daylighting systems present and computational time expenses.

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NOMENCLATURE

$d_k$ Daylight coefficient.
$L_k$ Luminance (cd/m2).
$a_k$ solid angle (sterad)
$R_1$, $R_2$ Random numbers.