QUICK DETERMINATION OF DAYLIGHT AND IRRADIANCE IN A ROOM WITH LIGHTSHELF AND ITS APPLICATION TO A HOT HUMID CLIMATE

Eduardo Breviglieri Pereira de Castro
Prof., M.Sc., Instituto de Ciências Exatas,
Universidade Federal de Juiz de Fora, UFJF, FAU/UFRJ.
e-mail: edubrevi@jfa.nutecnet.com.br

Leopoldo Eurico Gonçalves Bastos
Prof., D.Sc., E.E./COPPE/Faculdade de Arquitetura e Urbanisno, FAU/
Universidade Federal do Rio de Janeiro, UFRJ.
CP 68503, 21.945-970 Rio de Janeiro, BRAZIL
FAX 5521-290-6626, e-mail: leopoldo@serv.com.ufrj.br

ABSTRACT

The aim of this work is to present a simulation programme for PCs which is easy to use and yields quick results of daylighting along the day in an indoor environment provided with a lightshelf, and solar irradiation levels on the external façade of a building. The programme was developed aiming simulations for hot humid climate conditions.

The calculations are performed under three sky conditions for a selected site, albedo, surface orientation and inclination, window and lightshelf characteristics, room dimensions and wall surface reflectances.

A case study is presented for the Rio de Janeiro city, where the performance of a lightshelf is determined in order to reduce glare and solar gain near the window, and to increase natural lighting at the rear of the room.

1. INTRODUCTION

The evaluation of daylighting and solar energy incidence inside an interior building space provided with a lightshelf fenestration system is a theme of permanent interest.

In tropical climates this system can provide energy conservation and comfort by reducing thermal loads, glare and improving the natural lighting distribution inside the room. From figure 1 it can be observed the influence of a lightshelf on the interior daylight illumination.

In spite of this importance, the use of lightshelves has not spread yet in hot climate areas, perhaps due to the difficulties in analyzing its performance along the year. Previously, some authors have treated from a computational point of view the lightshelf element: Miller et Alii (1992) presented daylighting design via Monte Carlo method through the computer code DAY3D. Results are shown for a specular surface lightshelf. Sorensen and Madsen (1995) gave some results of lightshelf fenestration by means the computer programme ADELINE. Also, some computer applications in Europe were described by Strachan (1996).

The present paper deals with a simulation computer programme specially designed to evaluate the behavior and performance of a window provided with lightshelf inserted in a box-type building room and under hot humid climate conditions. The advantage of this software is its user-friendliness and that it allows quick determination of interior daylighting, solar irradiance and lightshelf performance.

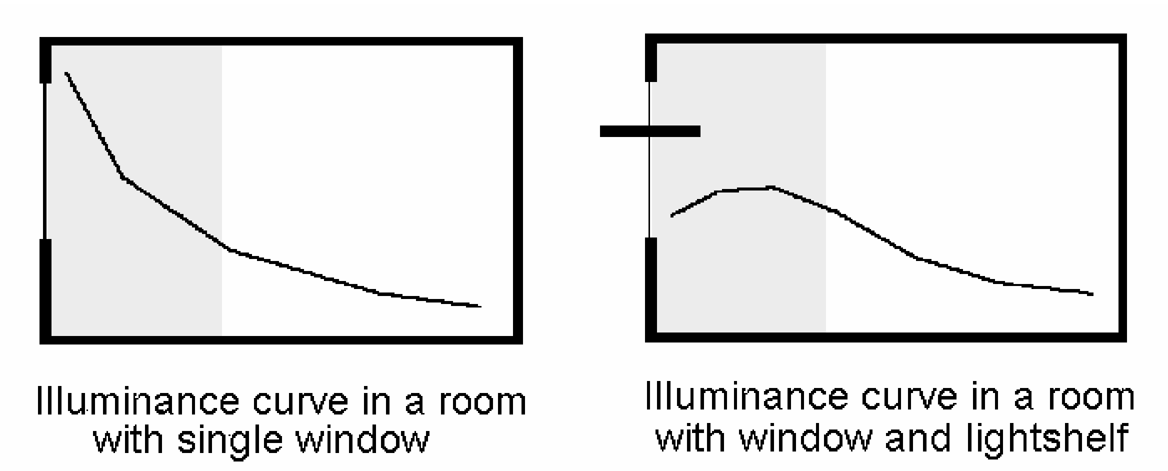

Figure 1 - *Schematic draw about the lightshelf influence*

2. CHARACTERISTICS OF A LIGHTSHELF

A lightshelf is an architectural element that can improve the daylight distribution in ambients only illuminated by windows. Also, due to the shading effect, glare is reduced and energy conservation and thermal comfort can be reached.

The lightshelf has a peculiar aspect: it is a horizontal surface (slab) inserted in a window frame dividing it in two portions (upper and lower) and presenting interior and exterior protrusions. The interior portion penetrates into the room and appears to someone as an illuminated shelf. This interior protrusion has the function to carry by reflection the natural light entering the upper portion of the window to the rear of the ambient. Then, it is provided for the increase of interior daylighting illumination levels and more uniformity along the room.

The geometric dimensions for a lightshelf inserted in a given window are: internal and external overhang depths, thickness of the slab and its position given by the vertical height taken from window sill. Also, the finishing and painted color of the lightshelf influence the reflective properties of its surfaces. In this work, only lightshelves with diffuse reflections are considered and the lightshelf surface reflectances must be known in order to the calculations be performed.

3. THEORETICAL APPROACH

3.1 *Irradiance and Sunlight Modeling*

The computer programme developed firstly determines for a chosen date and along the day the levels of solar irradiation (W/m^2) and natural light (lux) incident on an exposed oriented surface at a given site location. The theoretical solar energy model of Dogniaux (1985) is here adopted. This model requires as input data for the site: latitude, longitude, altitude above sea level, local climate, type and albedo of the surrounding environment, and luminous efficacy. The climate and the type of environment (urban, rural or industrial) determine the local atmospheric turbidity. The programme also has an option to calculate the turbidity by the L'Omm method, which is based on the clearness and color of the sky (according to Castro, 1995). For the surface data the inclination from the horizontal plane and the azimuth angle are needed.

The calculations are performed considering three sky conditions: perfectly clear (no clouds), the CIE overcast (completely cloudy), and variable (partially cloudy).

Considering as an attempt to validate this model for Rio de Janeiro, a comparison was made between the calculated results for the monthly average total irradiation on horizontal surfaces and the measured data from Cavalcanti (1991). It was obtained a year average ratio of 1,69% (see figure 2) indicating this model can be used in simulation studies.

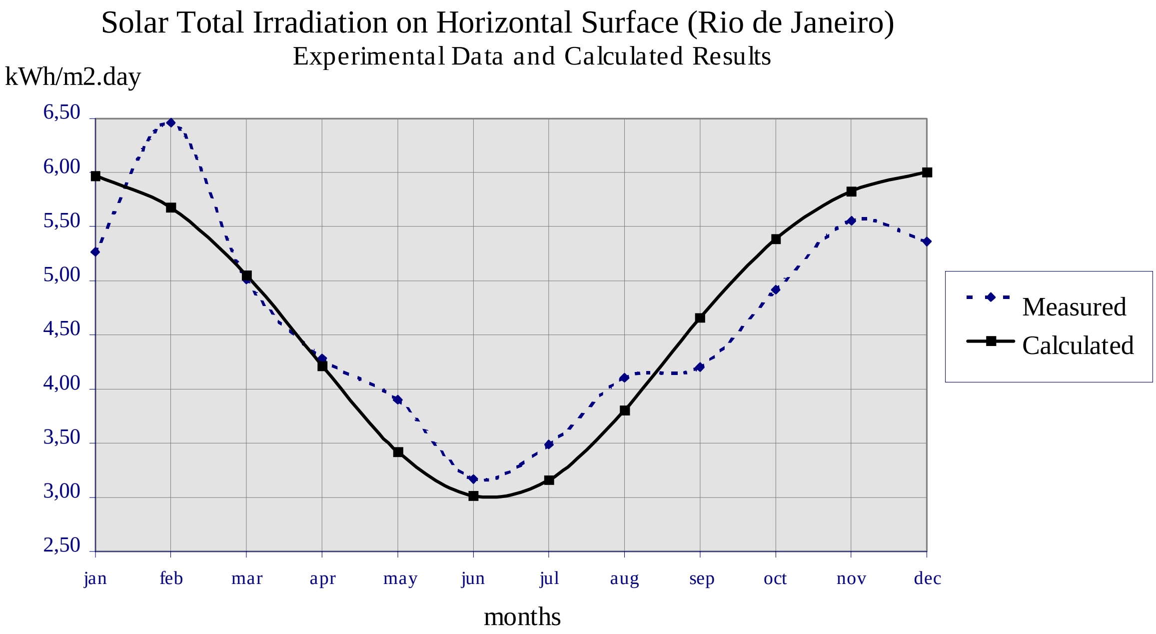

Figure 2 - *Comparison between monthly average solar irradiation experimental data and calculated results*

To validate the luminous efficacy for Rio de Janeiro, a comparison was made between the calculated results for the yearly average external illuminance on an horizontal surface and the data presented by Mascaró (1991). For clear sky conditions, the difference obtained was less then 14,4% (measured:64150 lux; calculated:73400 lux). For overcast conditions, the difference was 8,9% (measured: 24100 lux; calculated:22150 lux). These calculated results were obtained using Dogniaux standard values for clear-sky and overcast-sky luminous efficacy, i.e., 106.97 lm/W and 126.08 lm/W respectively.

3.2 *Daylight Components*

Design process of daylighting systems requires some knowledge about the exterior available light in terms of quantity and quality. The light coming from the sun and the diffuse component from the sky dome that reaches an interior point of the room are dependent on the visible portion of the sky seen from that point through the opening. Thus, in addition to the quantity of light, natural lighting also depends on aperture or fenestration shape, window location on the wall and window glazing.

Basically, the natural light reaching an inner point is due to four distinct light components. The first is the *direct component* from the sun, incident on the point without any obstruction interference. The second one is the *diffuse sky component*, resulting from the sun rays scattered in atmosphere. The third component is the *exterior reflected component*, which is the amount of exterior light reflected by surfaces, trees, soil, water that can reach the interior point. The last light component, the *interior reflected component*, is that reaching the considered point and coming from the other illuminated inner surfaces acting as secondary light sources.

3.3 *The Illuminance Model*

Daylighting calculations for a selected point inside the room can be performed using the finite surface method. According this approach the incident light is dependent on the incident sun rays attenuated by the glazing transmissivity and on the other daylight diffuse components calculated with the help of the configuration or view factors between surfaces.

When there is not direct incidence of the sun rays on the considered point, it is considered the window panel radiosity, i.e., the energy flux leaving it. So, the light striking an interior point depends on the solar radiation entering the room and on the radiation exchange between the infinitesimal surface (point) and the other building surfaces.

A Configuration Factor is defined as the fraction of the energy that comes diffusely from a surface “A” and strikes a surface “B”. These surfaces “A” and “B” may be extensive or infinitesimal ones, and may be freely oriented. So, the configuration factors can be calculated for a great number of situations, allowing the simulation of very complex geometry rooms. In the specific case of natural light reflection calculation inside buildings two configuration factors are used (see figure 3):

1) Configuration Factor between a source rectangular surface “A” and a small target plane “B” (a point), “A” and “B” *parallel* to each other, “B” standing directly under one of surface’s “A” vertices.

2) Configuration Factor between a source rectangular surface “A” and a small target plane “B” (a point), “A” and “B” *perpendicular* to each other, “B” standing directly under one of surface’s “A” vertices.

When the target plane is an extensive surface, like in the calculation of light reflections between walls or two interior planes, this target surface is divided into small rectangular areas and the calculation must be performed to the geometric centers of these areas.

The two configuration factors equations are:

Configuration Factor between two parallel surfaces (type 1):

$\mathbf{C} = 1/2\pi\ [A/(1+A^2)^{1/2}\ .\ \arctan\ (B/(1+A^2)^{1/2}) + B/(1+B^2)^{1/2}\ .\ \arctan\ (A/(1+B^2)^{1/2})]$

where: A = h/d e B = w/d

Configuration Factors between two normal surfaces (type 2):

$\mathbf{C} = 1/2\pi\ [\arctan\ (1/B^2) - B/(A^2+B^2)^{1/2}\ .\ \arctan\ (1/(A^2+B^2)^{1/2})]$

where: A = h/w e B = d/w

In the previous equations, ***d*** is the distance between the target plane B and the source surface A, ***h*** represents the height of surface A and ***w*** the width of surface A.

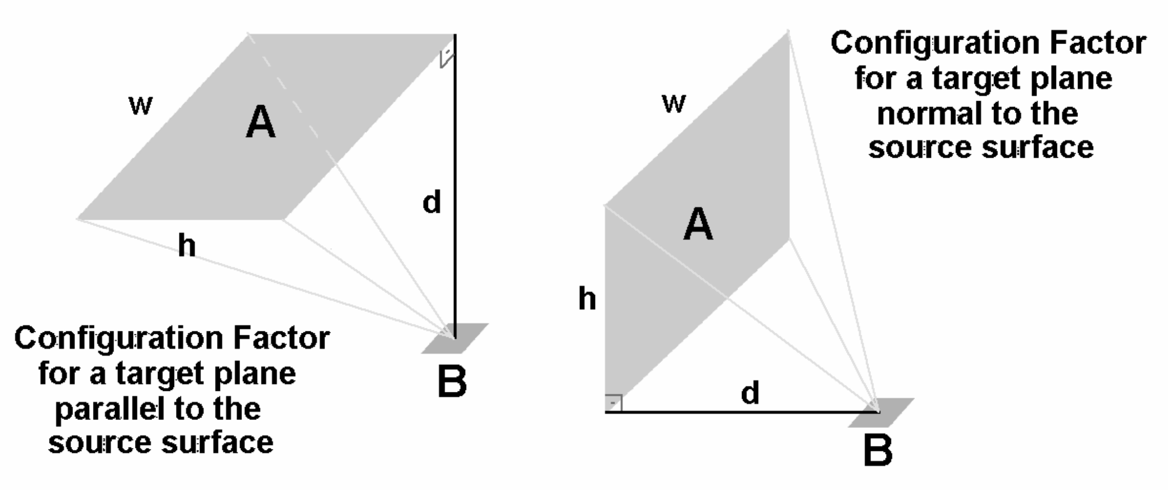

Figure 3 - *Configuration Factors*

4. THE SIMULATION PROGRAMME

4.1 *Structure of the Simulation Programme*

A microcomputer programme named "Radlite" was setup using all the models described above. The general idea was to develop a flexible tool to allow the study of any window provided or not with a lightshelf system. The software can be divided in three different parts, according to their operational functions (figure 4).

The first one is the graphical interface where the user can enter and modify some simulation's parameter, site, room, window and lightshelf geometry, and some solar radiation efficiency variables. The graphical interface has in addition the function of displaying the simulation results through the computer monitor under numerical or graphical plot. The interface is fully window oriented and runs only under Microsoft's Windows 3.XX or Windows 95.

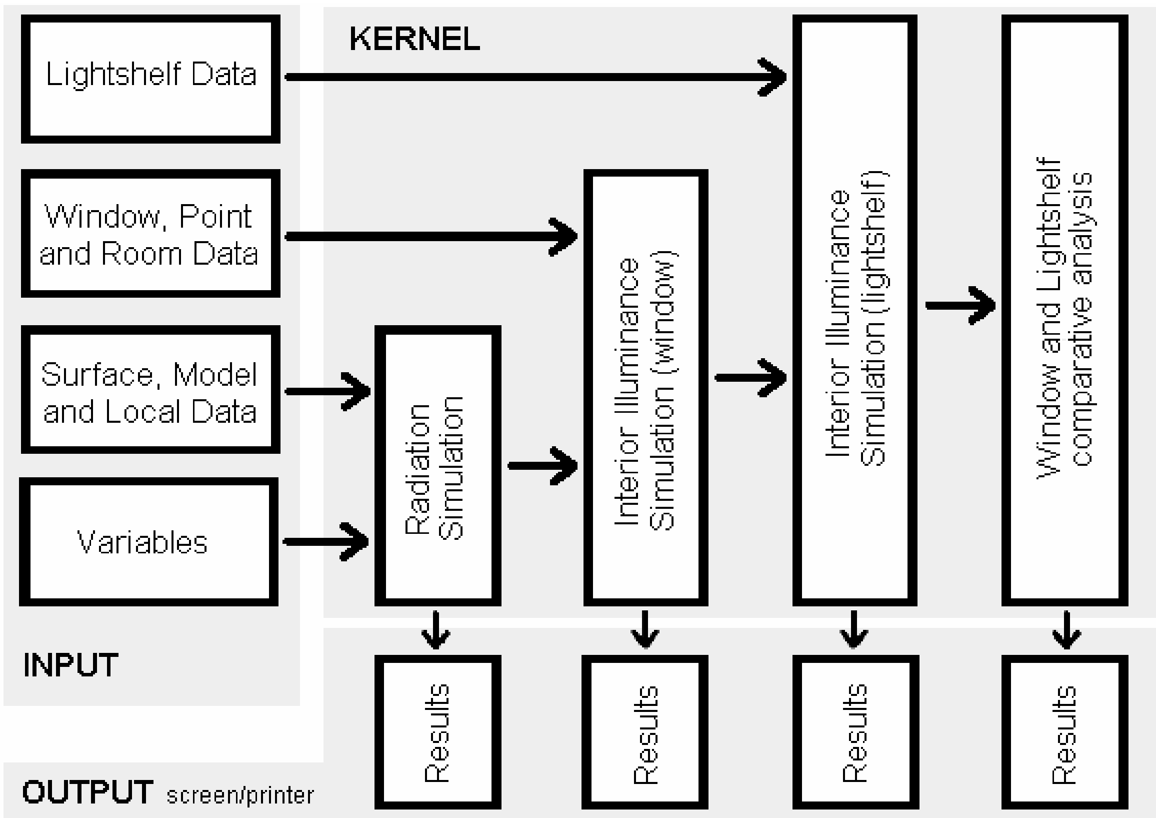

Figure 4 - *Structure of the simulation programme*

The next programme module is the kernel, containing all the theoretical models and solving methods required to perform the calculations. This module is composed of four sub-models which are accessed by distinct buttons in the user interface. Sub-module 1 calculates the solar irradiation incident on the building façade. Sub-module 2 calculates the illumination levels inside the room due to the existing window, and sub-module 3 determines the daylighting due to the window-lightshelf system. Sub-module 4 performs a comparative analysis between the presence or not of the lightshelf inserted in the window. For the single window simulation, only the direct components and first interior reflections are considered in the calculation of the illuminating levels, i.e., the programme calculates the natural light striking the point and striking the wall surfaces and then the portion of light that comes from these surfaces that reaches the reference point. The high-order several reflections between the interior surfaces are not considered. By other hand, for the window-lightshelf system, the daylight components are intercepted and the lightsehlf acts as a secondary source of light. In this case, besides all the components calculated for the simple window simulation, another interior reflection component is considered, due to the presence of the architectural element. The programme considers the lightshelf has two distinct functions as a secondary light source: a) its upper surface is a diffuse light emitter which will illuminate the ceiling and the upper surfaces of the room walls (which will then reflect this light to the sensor points) and; b) its lower surface is a secondary light source which will reflect the light that comes from the exterior soil surface and then reach the sensor points.

The third and last part of the programme is the output module which is basically a printer report generator. Depending on the user choice, the printed reports show from a single sheet list of the input data, to the complete set of simulated results under a table form or charts.

4.2 *Programme Utilization*

The developed software can calculate the illuminance levels inside any box-type room, in which a window is inserted in its main wall, this one defined as the surface which is directly exposed to the exterior (façade). Two kinds of simulations can be performed: for a single window and window-lightshelf system. Exterior solar radiation levels on the façade are also displayed.

The first thing to be done by the user is to input all required data through the respective programme windows. If this procedure are neglected and nothing is entered, the programme assumes the default values for the variables and parameters. There is also the possibility to restore some data from disk, if a simulation data file (.rlt proprietary format) has previously been saved.

The second procedure must be the calculation of the solar radiation striking an exterior surface. That is done by pressing the appropriate button in the user interface. After some calculation time (about 12 seconds in a Pentium 75 MHz machine) the results are displayed under a table format. The corresponding graphics are available by pressing a specific button of the window. By closing this programme screen the user is allowed to perform the simulations of daylight (interior illuminances) inside the room. The user can choose between a simulation for single window or a window with lightshelf, depending on the button pressed. Results are promptly displayed, in the same formats of the radiation simulation screen.

All the values calculated in the two previous steps (window and lightshelf simulations) are stored in the computer memory in order to make possible the comparative analysis, which is the fourth step of the simulation process. The results of this comparison are displayed under table and graphic formats. The values in the screen are the ratio between the illuminances of the window-lightshelf system and the single window. Thus, values higher than one denote higher illuminances with the use of the lightshelf, while numbers smaller than one denote a reduction in the illumination level at the reference point. A quality analysis is also performed, considering the following criteria: the lightshelf is considered efficient if it shadows points where direct sunlight is present.

As a final procedure, all the input data, simulation results and comparative studies can be printed to allow further analysis.

5. RESULTS AND DISCUSSION

5.1 *Selected Parameters*

In order to present some results from simulations performed, the following characteristics for the studied room (figure 5) are defined and the other required simulation parameters are presented:

Room Dimensions: 4,00 x 8,00 x 3,50 m;
Reflectivities: walls (0,70); floor (0,20); ceiling (0,80);
Window dimensions: 4,00 x 2,10 m localized at 0,90 m from the floor;
Type of glass: transparent with transmissivity of 0,90;
Window frame obstruction: 10%
Vertical height from the inferior side of the lightshelf to the windows sill: 1,55 m
Lightshelf thickness: 0,05 m;
Internal and external overhang depths: 0,50 m;
Lightshelf reflectivities for inferior and superior faces: 0,80;
Environmental albedo: 20%
Coefficient of Turbidity: 0,660 (calculated by the programme according to the Temperate climate and Urban environment parameters);
Reference height from the floor plane (point position): 0,75 m;
Dogniaux Clear-sky luminous efficacy: 106,97 lm/W;
Dogniaux Overcast-sky luminous efficacy: 126,08 lm/W.

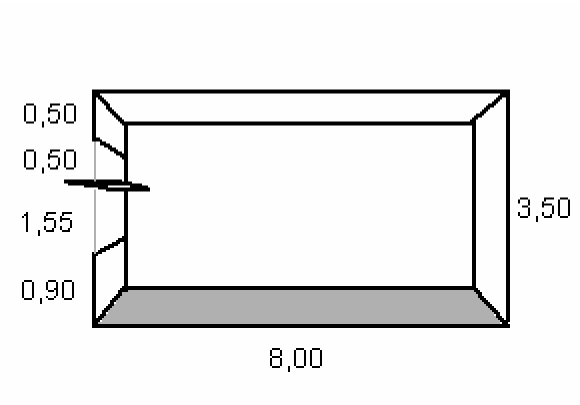

Figure 5 - *Cross Section of the Studied Room (distances in meters)*

5.2 *Software Validation*

Trying to validate the software Radlite a simulation was performed for a site in the north hemisphere (Latitude +30^o, longitude 40^o W and altitude 2,00 m above sea level) being the room façade oriented to the south. The simulated month was march. The considered window does not present a lightshelf. The results obtained were compared with results obtained with the programme SuperLite 2.0 for the reference room previously defined.

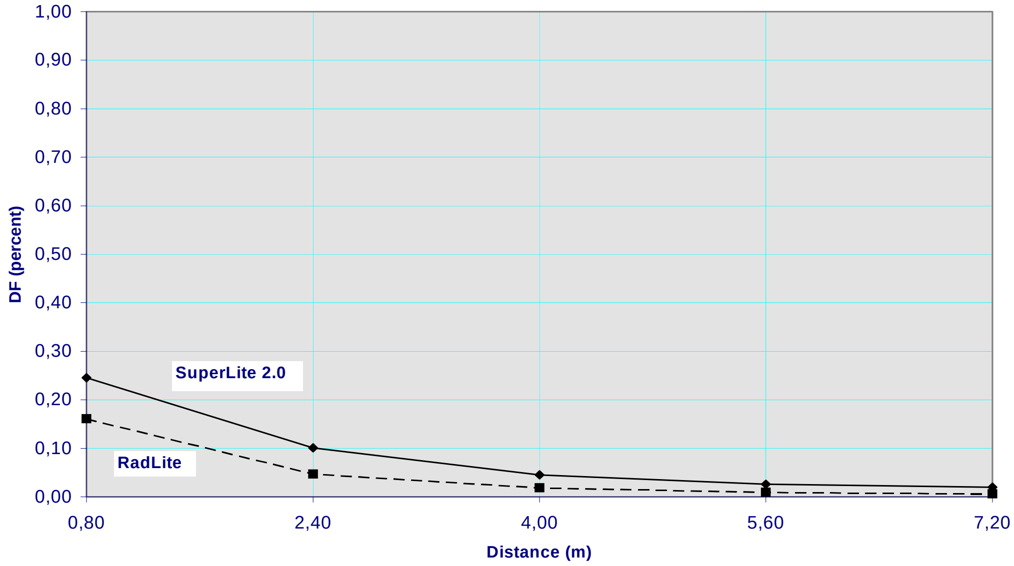

Figure 6 - *Illuminances Profiles in a Room with south facade.*
- Radlite and Superlite Simulations for Overcast Sky 11:00 h -

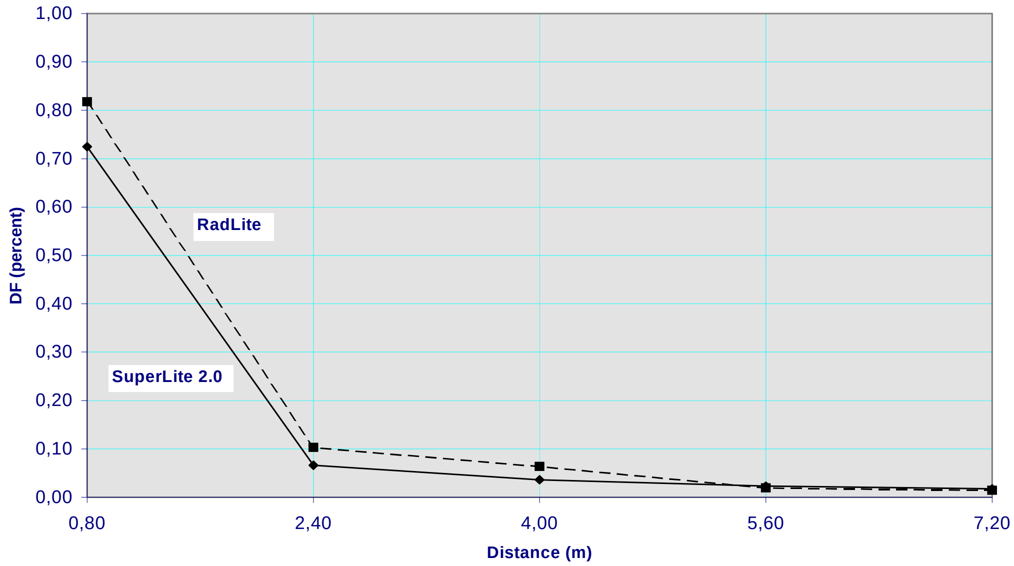

Figure 7 - *Illuminances Profiles in a Room with south facade.*
- Radlite and Superlite Simulations for Clear Sky 11:00 h -

It can be seen from figure 6 and 7 that for both situations (overcast and clear sky) the obtained results from the Radlite and Superlite 2.0 present similar behavior for the Daylight Factors. The existing differences between de Daylight Factors for a site from the two programmes can be explained perhaps by the type of considered theoretical approaches, computer codes, luminous efficacy values in default. For example, the

SuperLite's input mode that was used to simulate the window, does not accept luminous efficacy entries, and the user is not able to see them even in post-simulation outputs.

It can be observed that this work has the aim to describe the use of the software Radlite in studding the lightshelf application in hot humid climates. It needs to be mentioned that are in progress an effort to validate the theoretical results by means of experimental measurements under several sky conditions.

5.3 *Results and Discussion*

A case study is now presented for a room located in Rio de Janeiro (latitude 22,90^o S, longitude 43,17^o W, hot humid climate area) being the lightshelf wall oriented to the north. With the help of the software Radlite it is possible to analyze during the day and the year the performance of a lightshelf in comparison with a façade with single window. Several studies can be performed related to the variation of the lightshelf dimensions and orientation on its performance, as example: shading effect and lighting distribution inside the ambient, monthly performance evaluation, influence of the façade orientation, influence of the external and internal overhang depths, etc. The result charts are presented in terms of Daylight Factors for the illuminance profiles or dimensionless values for the lightshelf/window performance ratio. The Daylight Factor here adopted, in accordance with Robbins (1996), is calculated considering all daylight components, i.e., direct, diffuse sky, exterior reflected and interior reflected components. The coefficient of turbidity was calculated by the programme according to the tropical climate and urban environment parameters;

Corresponding to the shading effect and daylighting distribution inside the studied ambient, several simulations were made to obtain the longitudinal illumination profile following a perpendicular line to the building façade passing through the geometric center of the room. Nine points were object of simulation considering or not the lightshelf. The selected month was march due to the average sun declivity and thus representing a period having an average solar irradiation on the building envelope. Also, the combination north oriented façade/month of march, indicates a lot of distinct skies and solar irradiation for the considered site. The simulations were performed for overcast and clear skies conditions, at 9:00 and 12:00 h. Due to the fact that the lightshelf operates producing shading effect (interior points near the façade) and natural light redistribution inside the room, the first situation can be simulated considering it as a balcony, that is, a lightshelf with zero reflectivity. Figure 8 shows the performances for an overcast sky when the single action is to cut the direct incidence of the sun rays along the room axis. Figure 9 presents the illumination profile for the some case, indicating that near the façade the glare can be eliminated.

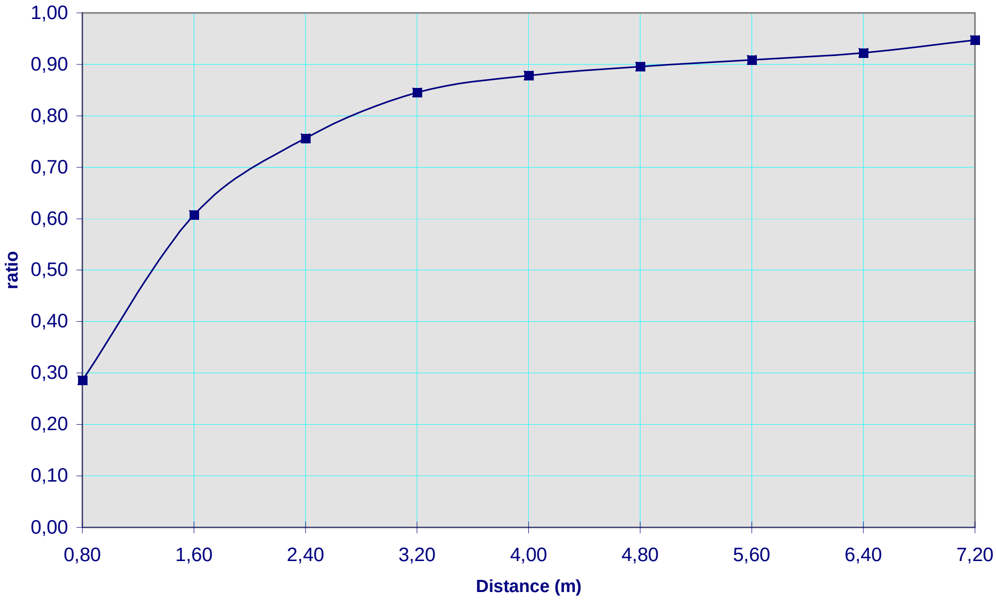

Figure 8 - *Lightshelf Performance (Lightshelf/Window Ratio)*
- Lightshelf reflectances = 0 - Overcast Sky - 9:00 h -

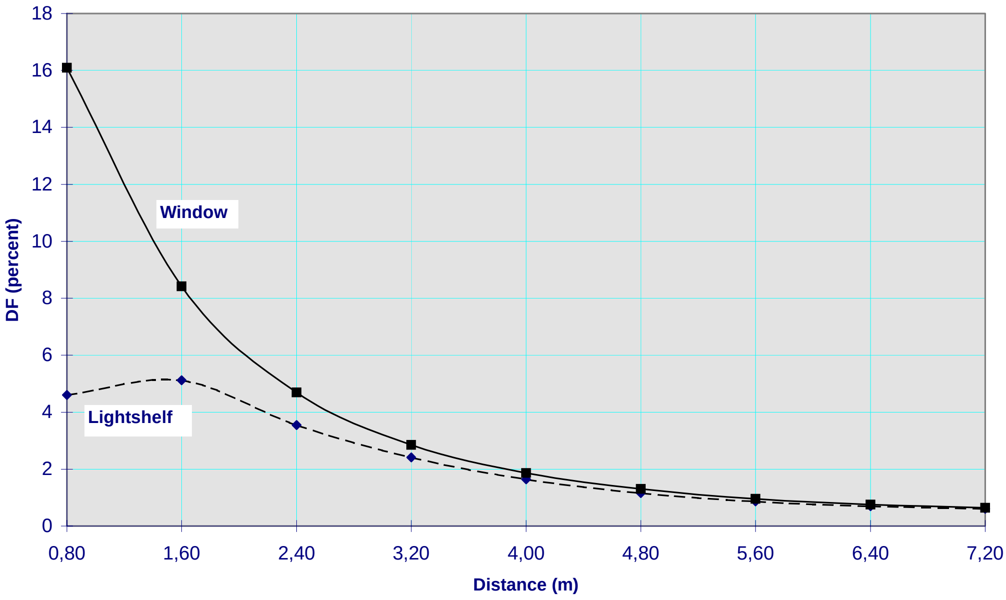

Figure 9 - *Illumination Profiles in a Room with Lightshelf.*
- Lightshelf reflectances = 0 - Overcast Sky - 9:00 h -

Now taking in account the lightshelf acting as a light reflector, the results are presented in the figure 10 as Daylight Factors at 12:00h for clear and overcast skies. It was used a lightshelf surface reflectivity of 0,80. Figure 11 shows the performances obtained for both sky conditions.

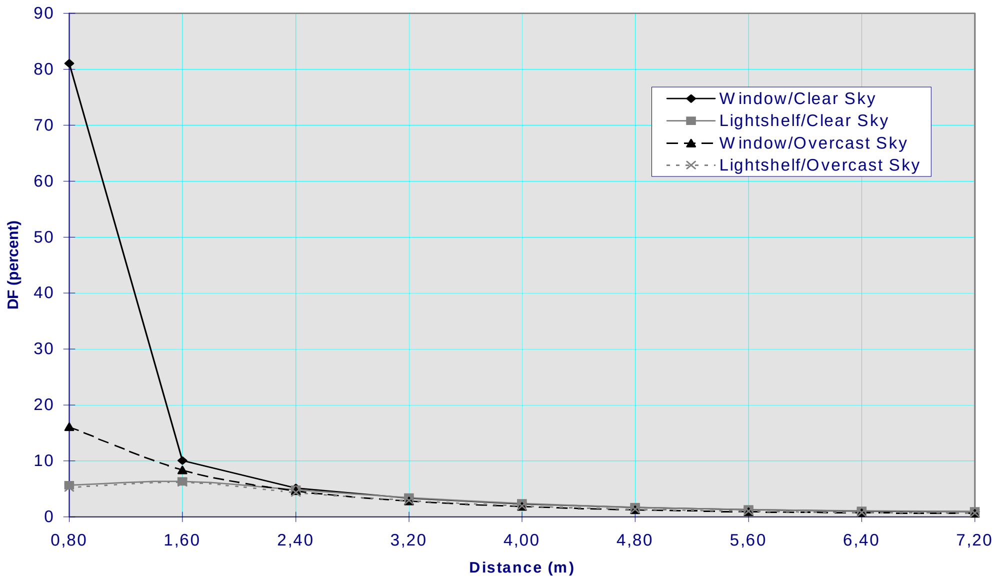

Figure 10 - *Illumination Profiles in a Room with Lightshelf.*
- Clear and Overcast Sky - 12:00 h -

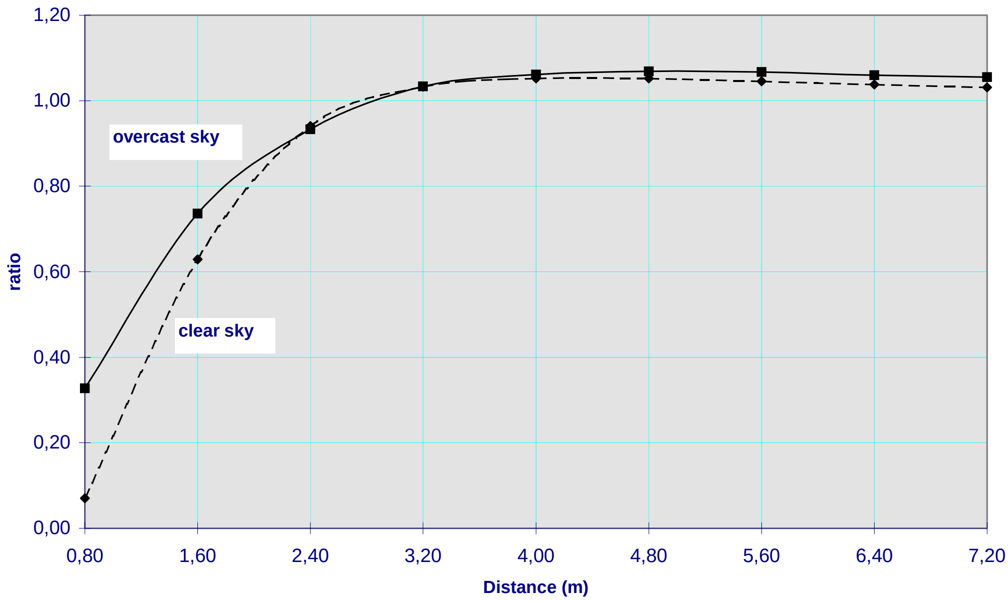

Figure 11 - *Lightshelf Performance (Lightshelf/Window Ratio)*
- Clear and Overcast Sky - 12:00 h -

The monthly performance of the lightshelf was studied for a point located 4,00 m from the façade where is the geometric center of the room and the performance obtained from the previous simulations indicate there is a maximum. The results are presented in figure 12, at noon and for overcast and clear skies. It can be observed from the results that for a clear sky condition there is an enormous variation of the lightshelf performance along the year at the considered hour of the day. The same behavior obtained for 9:00 and 15:00h is not presented here. For the overcast sky condition the performance is almost the same during the year.

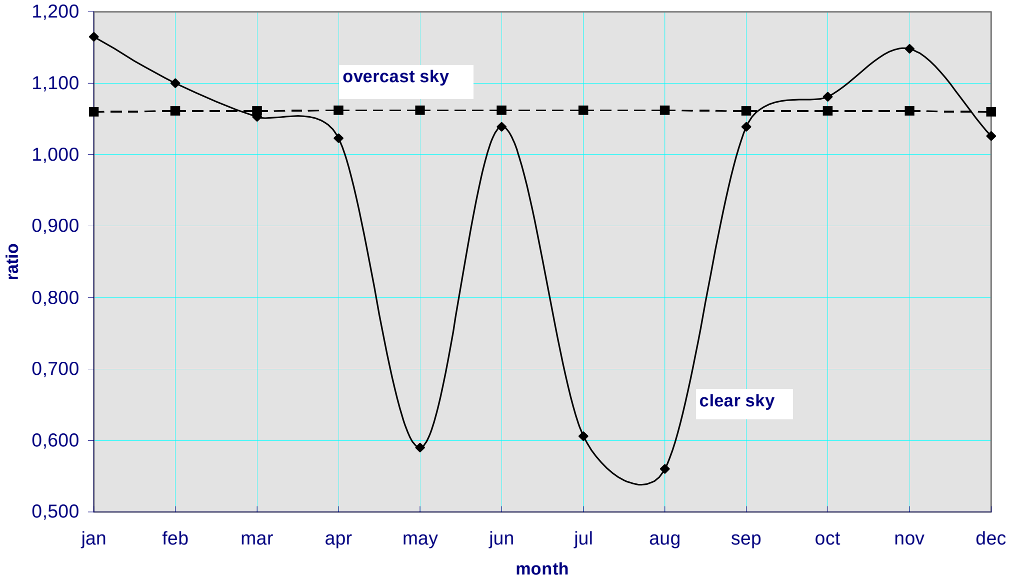

Figure 12 - *Monthly Performance of a Lightshelf - Clear and Overcast Sky - 12:00 h*

The influence of the façade orientation was verified for the month of march under a clear sky condition and at 9:00, 12:00 and 15:00 h. The results are in the figure 13. From these chart it is observed a higher performance during the morning and afternoon hours than at midday. For the month of march, there is always an increasing of the illumination levels (performance > 1) whatever the orientation considered.

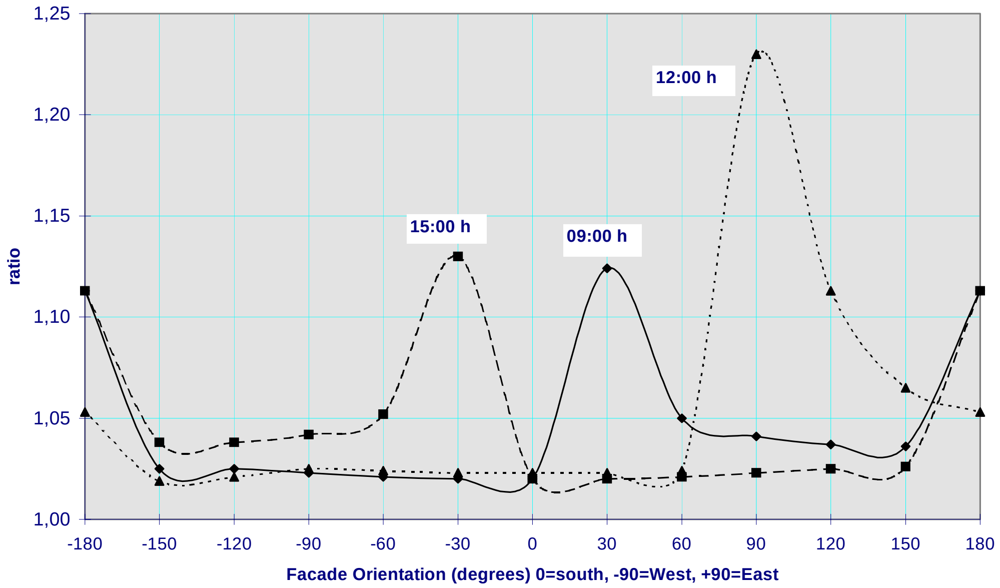

Figure 13 - *Lightshelf Performance and Façade Orientation (Lightshelf/Window Ratio) - Clear Sky - 9:00, 12:00 and 15:00 h*

The last simulations results deal with the performance evaluation due to the variation of external and internal surfaces of the lightshelf, considering the month of march, a point 4,00 m distant from the façade wall and a room façade oriented to north. It is considered a fixed depth of 0,50 m for one protrusion while the other side is varied from 0.3 to 1.0 m (figures 14 and 15). The results for clear sky conditions indicate the external protrusion is efficient in shading the room areas near the windows while the interior portion of the lightshelf is efficient in the light redistribution effect. Overcast sky simulation shows the same results.

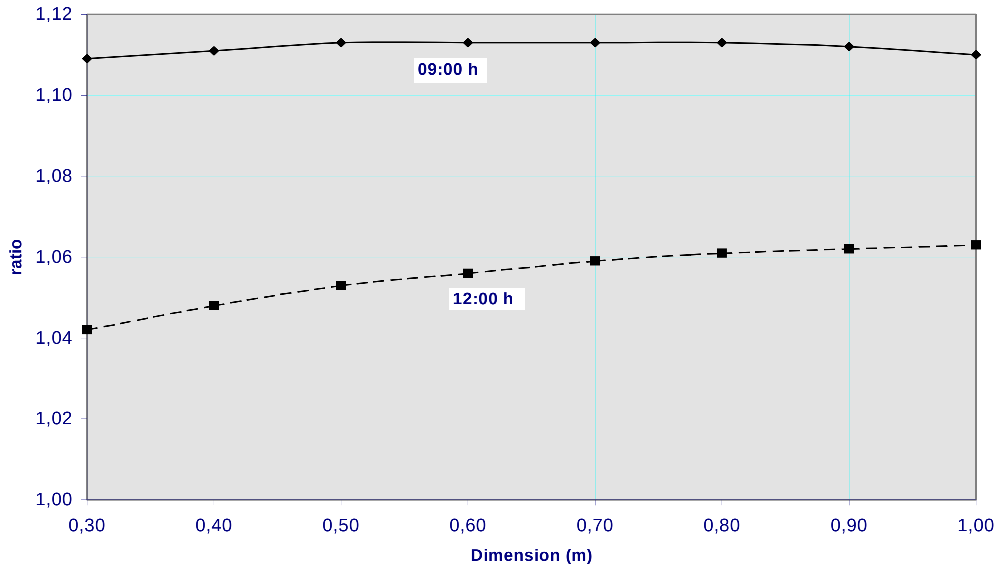

Figure 14 - *Lightshelf Performance and External Protrusion Dimension (Lightshelf/Window Ratio) - Clear Sky - 9:00 and 12:00 h -*

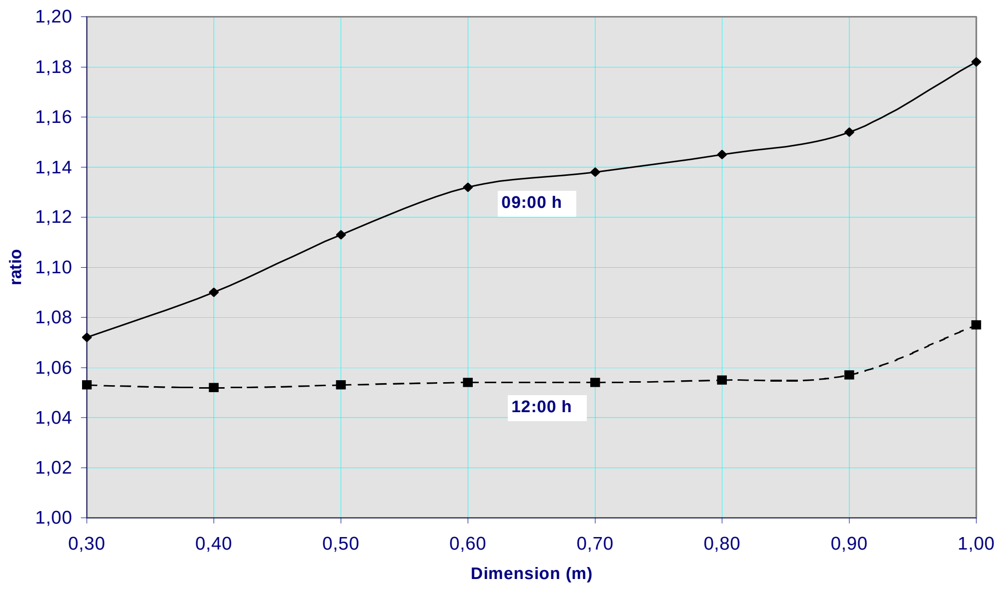

Figure 15 - *Lightshelf Performance and Internal Protrusion Dimension (Lightshelf/Window Ratio) - Clear Sky - 9:00 and 12:00 h -*

CONCLUSIONS

The case studied presented and the simulations performed make it possible to realize the real advantages of the use of a lightshelf under tropical climate conditions. In these regions, the great architectural problem is to provide shading elements to the building in order to prevent the direct incidence of sun rays inside the ambients (thus reducing the thermal loads). Generally, these elements also reduce the illumination levels in the interior areas of the building. From this point of view, the lightshelf can be very efficient because it provides shading without sacrificing the illuminances of the interior spaces.

The computer programme that was developed allows us to predict illuminance levels inside any box-type room in which the source of light is a single window or a window with lightshelf. The interactive user's interface and the small amount of time required to perform the calculations, make the software a very useful tool to simulate the effects of the utilization of lightshelves in daylighting systems in the early phases of the architectural design process. The small size of the software (less then 750 Kbytes) and the choice of running it under a popular operational system, also allows its utilization on any Intel-based platform.

Further studies may contribute to increase the lightshelf development and comprehension by analyzing for example, the influence of inclining the external portion of the element to achieve a greater performance in the rear of the room. Also, since there was a difference of about 10% between the simulated results encountered and the few available illumination data, it is clear the need for a deeper study in adjusting the simulation tool to a new set of experimental data.

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