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Solar radiation calculation methodology for building exterior surfaces

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Abstract

The present article shows a new methodology of calculation of the direct, diffuse and reflected incident solar radiation, in all type of surfaces, either in open urban environments or inside buildings. This methodology is applicable in problems related to solar access (space heating in buildings, shadowing of open spaces), solar gains (space cooling in buildings), and daylighting. Solar radiation is the most important contribution to the surface and volumetric energy balance during the daytime. Particularly, solar radiation is the main contributor to heat gains in buildings, especially in residential buildings, where internal gains are very low. Utilization of daylight in buildings may result in significant savings in electricity consumption for lighting while creating a higher quality indoor environment. Additional energy savings may also be realized during cooling season, when reduction of internal heat gains due to electric lighting results in a corresponding reduction of cooling energy consumption.

The analysis of the existing calculation methods and proposed in the scientific bibliography for the calculation of the solar radiation in problems of solar access in winter, solar gains in summer, and daylighting, takes us to the necessity of outlining a new and complete methodology. This new methodology is applicable to all these problems with a great accuracy and calculation speed.

Keywords: Solar radiation; Backward ray tracing; Urban environment

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1. Introduction

The present article shows a new methodology of calculation of the direct, diffuse and reflected incident solar radiation, in all type of surfaces, either in open urban environments or inside buildings. This novel model was developed and presented by the author of the article for his doctoral thesis (Sánchez, 2003) and it is based on a characterization methodology.

The generality of the methodology, here explained, makes it useful in all those problems where it is necessary to calculate the incident total solar radiation on a surface. In the building sector, this methodology is applicable in problems related to solar access (space

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heating in buildings, shadowing of open spaces), solar gains (space cooling in buildings), and daylighting.

The importance of the study of these matters, as well as the necessity to quantify them in a reliable way, is clear in the huge number of articles in the scientific bibliography. Furthermore, a special attention is paid to the urban environment by its biggest complexity and differences in comparison with the rural one. These differences make that in an urban area less solar radiation is received than in its surroundings. As an example, in industrial cities, the loss in the duration of the solar radiation can be between the 10% and 20% (Landsberg, 1981; Chandler, 1965). The importance of this effect on the solar radiation received in the urban area is crucial, if one keeps in mind that almost the whole energy in the open spaces, comes directly or indirectly from the sun.

2. Solar access, solar gains and daylighting in the bibliography

In the study of the necessities of heating of the buildings, as well as for the comfort in external open spaces in winter, it is necessary to determine those areas that are in shade due to the buildings and other elements in the urban context. This study is of vital importance when an urbanization is being designed. With this motivation several parameters can be found in the bibliography. One of them is called 'sunlighting volume', that is defined as a set of sunbeams along a certain period of time, and is calculated as a geometrical problem since take into account only direct radiation. This parameter allows an easy to use representation, within a CAD system, of the shadings and shadows in an urban environment, and it seems to be useful in an architectural and urban design process (Siret and Houpert, 2004). Another parameter called 'solar envelope' states that buildings within this container will not overshadow their surroundings during critical periods of solar access for passive and low-energy architecture (Knowles, 2003). In a greater scale, an evaluation of the total annual/monthly irradiation incident on building facades in urban settings can be put as 'maps' in a geographical information system (GIS) based solar energy planning system. These 'maps' are targeted at city planners and one of its aims is to encourage the consideration of solar energy in the urban planning process (Mardaljevic and Rylatt, 2003). Among other software tools, one of the most cited is the computer program TOWNSCOPE (Dupagne, 1991), this program is found very useful to study solar access in obstructed situations, both within new developments and in existing buildings nearby (Littlefair, 2001).

Under refrigeration conditions, the problem is to determine the quantity of solar radiation absorbed by the spaces of the buildings. The solar radiation is, in general, the bigger responsible of the heat gains in a building, mainly in residential buildings, in those that the gains for internal sources are small. It becomes necessary, therefore, in many cases to limit these gains for solar radiation, using elements that shadow the external surfaces of the buildings, giving place this way, to an improvement of the interior comfort, and to a reduction of the costs for refrigeration (Littlefair, 2000). With the purpose of this study, different cases have been studied based on the radiosity-irradiation method. The results of these analysis show that a grid pattern that produces discrete surfaces having dimensions of less than 0.30 m yields accurate results (Wen and Smith, 2002).

Finally, the study of the solar radiation can be focused to the daylighting. The first step to give in the design for natural illumination in buildings is to assure that this illumination exists in the interior and exterior of the building in design, as well as of the adjacent buildings. This task can be carried out examining the position of the building proposed in its location place, determining the impact of the external natural obstacles in the distribution of the natural illumination, and finally determining this same effect but on the part of the external obstacles originated by the man. On the other hand, it should be kept in mind that the requirements imposed by the natural illumination, and for the limitation of thermal loads, they can be in some opposed cases. For the systems of natural illumination, the direct light can be necessary along the whole year. On the contrary, for the thermal applications, the solar access is desirable during the winter, but not in the summer.

Utilization of daylight in buildings may result in significant savings in electricity consumption for lighting while creating a higher quality indoor environment. Additional energy savings may also be realized during cooling season, when reduction of internal heat gains due to electric lighting results in a corresponding reduction of cooling energy consumption. These ideas are used with the objective to provide design and operating support for assessing the effects of large-scale uptake of solar technologies in urban settings (Stokes et al., 2004).

By coupling a daylighting simulation tool (ADELINE) and a dynamic thermal simulation software (TRNSYS), different office buildings have been studied showing the following results: daylighting can reduce artificial lighting consumption from 50% to 80% and as a consequence the reduction of lighting internal loads can then reach 40% (Bodart and De Herde, 2002). Another study of office buildings focus on the consideration of the interrelation between daylight, artificial lighting and thermal loads, show that about 30% of the energy consumption of office buildings can be saved by the use of daylighting (Franzetti et al., 2004).

The analysis of the existent calculation methods and proposed in the scientific bibliography for the calculation of the solar radiation in problems of solar access in winter, solar gains in summer, and daylighting, takes us to the necessity of outlining a new and complete methodology. This new methodology is applicable to all these problems with a great accuracy and calculation speed, and taking into consideration that is based on a method of characterization, it has its biggest advantages in the following cases:

- Urban environments with great number of surfaces.
- Great number of hours of calculation like it is the case of an annual analysis of the problem.
- Relevance of the multiple reflections among surfaces.
- Discretization of the surface under study allowing groups of different results in each node.
- Necessity of a quick and at the same time very exact result.

3. Characterization method

The method developed in this paper for the assessment of the solar radiation is a characterization method. This kind of methods divides the calculation process into two steps: pre-process and post-process. During the first step, pre-process, the sun is supposed to be in a set of different and known positions and the results are the ratios of the different components of the solar radiation among those positions and that over an horizontal surface. If the sky is considered isotropic, then the ratio corresponding to the diffuse radiation and reflected from the diffuse radiation are independents of the sun position. The accuracy of the whole method is controlled by this step, just increasing the number of sun positions and the number of rays for diffuse and reflected radiation, as it is explained in deep below.

The second and last step translates the previous calculated ratios to real values of the different components of the solar radiation. During this step the ratio corresponding to a certain hour, day and month, is calculated by interpolation among those calculated in the first step. This paper presents also a novel and useful graphical method for this interpolation in the following section. Once the ratio for each component of the solar radiation has been calculated by interpolation, this value is multiplied by the hourly amount of solar radiation over an horizontal surface given in this way the sought results.

A flow diagram of the whole process is shown in Fig. 1.

4. Solar positions

Provided isotropic sky, it is only necessary to save one data for diffuse radiation and one data for reflected or transmitted from diffuse radiation. In this case, for all solar positions the same single figure tells us the ratio of diffuse radiation that impinge over the surface in question directly or after being reflected or transmitted in another exterior surfaces in relation to the diffuse radiation over an horizontal surface.

As far as direct radiation and reflected or transmitted from direct are concerned it is clear that one single value is not enough, since these ones depend on the solar position. This problem is solved in a characterization method by saving the ratio of direct, or reflected from direct,

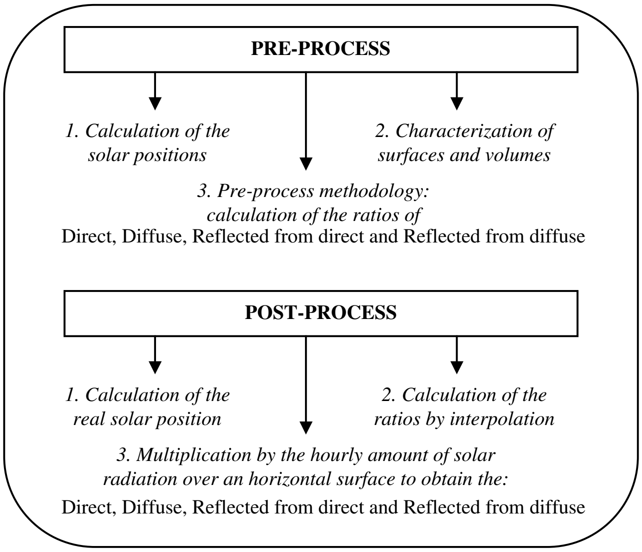


Fig. 1. Flow diagram of the whole methodology proposed.

radiation that impinge over the surface in question in relation to the direct radiation over an horizontal surface, for a set of different and known solar positions. Thus, the selection of this set of solar positions in the module for the assessment of natural lighting of the software tool DOE-2, consists on a total of 20 solar positions, which have been distributed uniformly in altitude and solar azimuth (Winkelmann and Selkowitz, 1985).

In Fig. 2, the 20 positions for the north hemisphere are shown. The result is an uniform distribution of five points from 70° to 290° from the north, and four points equally distributed in solar altitude from 10° (5° for latitudes higher than 48°) to the maximum solar altitude.

The main drawback of this distribution is the inclusion of unreachable points by the sun (see Fig. 2), to allow the interpolation with the real altitude and azimuth for a certain hour, day and month, when the thermal simulation program is running. To solve this drawback, a novel and useful graphical method for this interpolation is presented in this paper. The found solution uses the following change of variable:

$$\text{Altitude}^* = \frac{\text{Altitude}(12\,\text{h},\text{day},\text{month}) - \text{Altitude}(12\,\text{h},21\text{st},\text{Dec})}{\text{Altitude}(12\,\text{h},21\text{st},\text{Jun}) - \text{Altitude}(12\,\text{h},21\text{st},\text{Dec})} \tag{1}$$

$$\text{Hour}^* = \frac{\text{Hour} - \text{Sunrise Hour}(\text{day},\text{month})}{\text{SunsetHour}(\text{day},\text{month}) - \text{SunriseHour}(\text{day},\text{month})} \tag{2}$$

Now, it is possible to reduce the number of required solar positions in the pre-process and as a consequence the number of saved data and CPU time. The new graph of Altitude vs. Hour is shown in Fig. 3, where, Altitude* is 1 for the 21st of June and 0 for the 21st of December, and Hour* is between 0 and 1 for the sunrise and the sunset of each day, respectively. Using this graph, all the resulting points will correspond to feasible solar positions, and then, it is possible to reduce the number of solar positions to get the same accuracy.

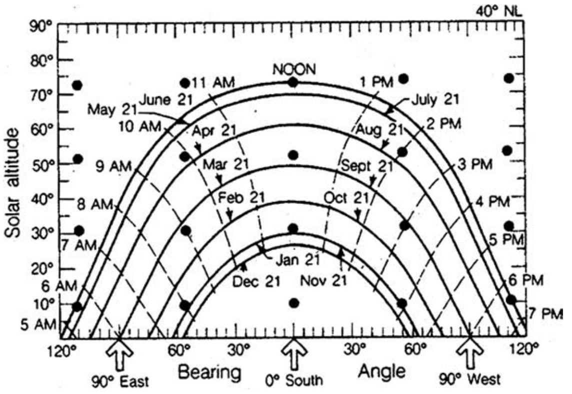


Fig. 2. Solar positions in the pre-processor of DOE-2. Latitude 40° N.

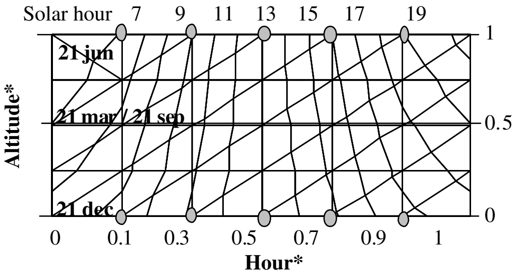


Fig. 3. Solar positions for the proposed method. Latitude 40° N.

In Fig. 3, days are represented by horizontal lines while vertical lines are fractions of days.

5. Characterization of surfaces and volumes

The directions of the rays of diffuse radiation that arrive to one surface follow a distribution that depends on the radiative properties of the emitter surfaces. On the other hand, the energy of each ray, or luminancy, depends on the ray direction too.

The heat flux by radiation that impinges in a surface depends on that distribution, and it is calculated using the following expression (see Fig. 4):

$$q_{s,i} = 2\sigma T_i^4 \int_0^{\pi/2} \varepsilon_i(\theta)\cos\theta\sin\theta\,\mathrm{d}\theta \tag{3}$$

Dividing by σT^4 and treating the surface as a black body, the next dimensionless parameter is obtained:

$$r = \frac{q_{s,i}}{\sigma T_i^4} = 1 - \cos^2\theta \tag{4}$$

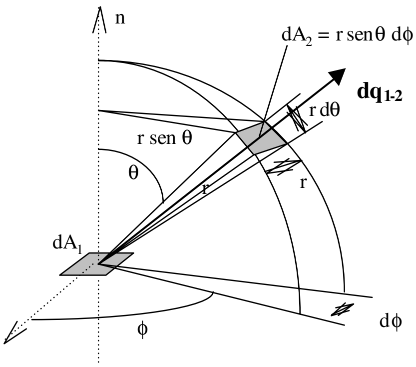


Fig. 4. Emission of radiation dq_{1-2} from a differential area dA_1 into a solid angle subtended by dA_2 at a point on dA_1.

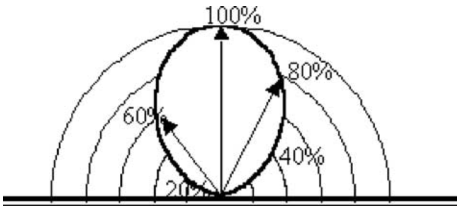


Fig. 5. Radiation emitted by a diffuse surface. Directional distribution.

Notice that this parameter could be obtained for a non-grey surface in a similar way.

Using this equation, it is possible to obtain the normalized distribution that corresponds to the diffuse radiant emission. Any set and number of rays that fit this distribution will allow considering each one of the rays as carrying the same energy (Incropera and de Witt, 1985). Also, this distribution can be used as incident radiation because in this case the heat flux equation that must be integrated is the same.

The way of cast the rays can be random, using the Monte Carlo method, but this method presents a high instability and can be incongruent if the number of rays is very low. Instead of a random distribution like that, this paper proposed to select the rays uniformly so as to the whole set of rays fit the distribution of diffuse emission corresponding to each surface. As the number of combinations is infinite, our proposal is to cast the first ray perpendicularly to the surface in question and to distribute the rest in the azimuth (ψ) and in the zenith (θ) directions. As ψ varies from 0° to 360° and θ from 0° to 90°, it seems a reasonable decision to select four times more rays in the first direction than in the second one. An example of this distribution for an horizontal surface can be seen in Fig. 5, where it is represented in percentages the number of rays that can be found from an horizontal ray to a certain inclination or zenith.

In a more general situation the method can deal with surfaces that not reflect or transmit radiation as a grey surface. This does not imply any additional difficulty to the methodology exposed here for the assessment of the different components of solar radiation, because, the only difference is that the previous equation cannot be used, and instead of that, the new distribution has to be calculated by another mean. The "Ray Controller" method (REVIS project, 2000) is proposed as a robust method to assess the reflectivity and transmissivity distribution bulbs for any surface or set of surfaces.

6. Preprocess methodology

The pre-process methodology consists on assessing the mentioned ratios of direct radiation, diffuse radiation, and reflected or transmitted from direct radiation or from diffuse radiation. For this assessment, the set of calculated solar positions and the previous rays distributions are used. In both cases the inverse path of these rays one by one is followed, and for this reason we have called this methodology as 'Backward Ray Tracing'.

The whole process is realized in the following steps:

(1) In order to calculate the *direct radiation* impinging over the surface in question, a certain number of rays is cast, the direction of these rays is obtained from linking the central point of the surface with the fixed solar positions (see Fig. 3). If one ray reaches the sun without collide with another surface, it means that direct radiation is not blocked in this instant over this point, thus, the fraction of direct radiation will be the cosine between the normal to the surface and solar direction divided by the cosine between the solar direction and the vertical.

(2) The rest of radiations are diffuse, reflected or transmitted from direct or diffuse. We are going to suppose that all of these will reach the surface in question as diffuse radiation. So, a huge number of rays is cast from the representative point of the surface, this set of rays should fit the normalized distribution of the diffuse radiant emission (see Fig. 5), in this way all the rays will have, in addition, the same energy. For each one of these rays, we follow the next protocol:

(2.1) If one ray reaches the sky without collide previously with other surface, this means that *diffuse radiation* from sky is not blocked in this point and for this direction, this ray increase the counter of number of rays of diffuse radiation from sky. The total sum of these rays divided by the total number of cast rays is the fraction of diffuse radiation that impinge in that point of the surface in question. At the same time, it is the view factor surface–sky.

(2.2) If, on the contrary, the ray does not reach the sky, it reaches other surface. In this case this ray will increase the counter of number of rays that starting from the surface in question impinged over the other one. The final value of this counter divided by the total number of rays cast from the surface in question will be the view factor between these surfaces. In addition:

(2.2.1) A certain number of rays is cast from the blocking surface, these rays result from link the intersection point of the impinging ray and the blocking surface with the fixed solar positions (see Fig. 3), If one ray reaches the sun without collide previously with other surface, this means that the *reflected or transmitted radiation from direct* is not blocked in this instant over this point, thus, the contribution to the fraction of reflected and transmitted from direct radiation will be the cosine between the normal to the surface and solar direction divided by the cosine between the solar direction and the vertical, multiplied by the reflectivity or transmissivity (according to the case), of the blocking surface. The sum of all the contributions for all the solar positions divided by the total number of cast rays from the surface in question is the fraction of radiation reflected and transmitted form direct.

(2.2.2) A huge number of rays is cast from the intersection point on the blocking surface, this set of rays should fit the normalized distribution of the diffuse radiant emission (see Fig. 5). The number of these rays that reach the sky is computed multiplied by the reflectivity or the transmissivity (according to the case) of the blocking surface. The previous sum divided by the total number of rays cast from the blocking surface is the contribution to the reflected and transmitted diffuse radiation. Finally, the sum of all of these contributions divided by the total number of cast rays following the diffuse normalized distribution from the surface in question is the fraction of *reflected or transmitted radiation from diffuse*.

The accuracy of the procedure depends on the number of the cast rays and the way they are cast. In the described method, two quantities of rays are used: the number of diffuse rays cast from the surface in question, and the number of diffuse rays cast after the reflection in a blocked surface. The first figure has to be higher than the second one.

The methodology has been explained supposing that there is only one point in the surface in question; this gives a good approximation when the obstacles are far away. In the presence of near obstacles it is necessary to repeat the methodology taking more representative points over the surface just by using an uniform grid. In order to find an accurate solution, the calculation must be repeated increasing the number of points and then the results has to be compared, the process will finish when the difference between one assessment and the previous one is lower than a threshold value.

7. Application of the methodology and results

The proposed methodology has been implemented in a software tool. Using this program, hourly values for the solar radiation over the external surface of a building can be obtained divided into its components: direct, diffuse, reflected from direct and reflected from diffuse.

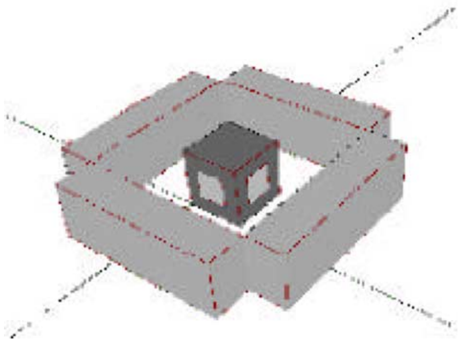


Fig. 6. View of the object building and its environment.

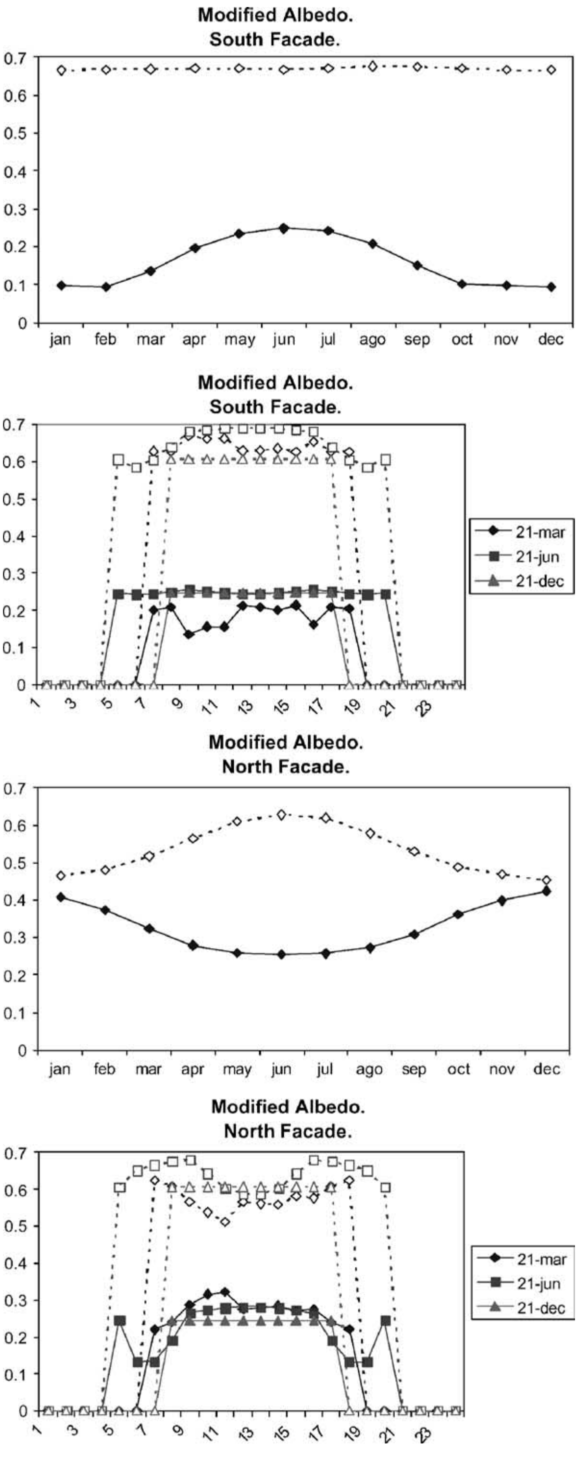


Fig. 7. Modified albedo graphs in South and North orientations. Yearly based and hourly based period.

Once obtained these values it is possible to compare them with the obtained values without deal with the external environment of the building and without using the proposed methodology. The reflected radiation without taking into account the environment of the building can be assessed as follows:

$$\mathrm{Rad}_{\mathrm{reflected}} = \rho \cdot (1 - \mathrm{VF}_{\mathrm{sky}}) \cdot (G_{\mathrm{b}} + G_{\mathrm{d}}) \tag{5}$$

where ρ is the average albedo or reflectivity of the environment. $\mathrm{VF}_{\mathrm{sky}}$ is the view factor with the sky. For a vertical wall in an open space it is 0.5. G_{b}, G_{d} are direct and diffuse radiation over horizontal surface respectively.

If the radiation assessed in this way is compared with the calculated taking into account the environment and following the proposed methodology, it is possible to define a 'modified albedo' (ρ_{mod}) as follows:

$$\mathrm{Rad}_{\mathrm{reflected}} = \rho_{\mathrm{mod}} \cdot (1 - \mathrm{VF}_{\mathrm{sky}}) \cdot (G_{\mathrm{b}} + G_{\mathrm{d}}) \tag{6}$$

In order to compare the results for the modified albedo with the results for the original albedo, an example has been studied. This example consists on a building of $3 \times 3 \times 3\ \mathrm{m}^3$, in which all the façades have one window of $1.5 \times 1.5\ \mathrm{m}^2$ in the centre. The orientations of the four façades are: north, south, east and west. In addition, in order to appreciate how the albedo is modified by the presence of obstacles, some buildings have been situated in front of the object building. These buildings have 3 m of height and the distance between them and the object building is 3 m too (see Fig. 6).

The results assuming an albedo of 0.7 for all the external surfaces of the building and its environment are shown in the Fig. 7, where, as it can be appreciated the values for the modified albedo are in all the cases lower than the original and, in addition, they depend on the orientation and the hour, month and day of the year. Solid lines show the values in the case with obstacles, discontinuous lines show the values in the case without obstacles.

8. Validation

The whole methodology, presented in this paper, and its software implementation in C++ language have been validated through a double process.

Firstly, using a quite simple configuration, an analytical validation has been possible based in the calculation of the view factors among different surfaces. Additionally, this validation has allowed to establish the relative importance of the different parameters controlling the methodology, like the numbers of rays, etc.

Secondly, a deeper validation of all the radiation components has been done using the measured results in an experiment focused on the calculation of daylight inside a room.

8.1. Analytical validation

To know the level of precision that the method reaches we proceed to compare the results obtained with the method, and the results obtained with an analytic solution. Analytic solution is based on the radiosity method. This limits our validation only to results obtained for the diffuse and reflected diffuse radiation. Also we can compare the results obtained for the form factors surface–sky, and surface–surface.

A scheme of the validation case is shown in Fig. 8 and it is composed by the ground, the sky, and two opaque surfaces separated 8 m. These surfaces have the same size (height: 2.4 m, width: 4.4 m). We will also suppose 1 W/m2 of diffuse radiation over a horizontal surface.

The analytic values that the form factor and diffuse and reflected diffuse radiation have in this situation are shown in Table 1.

We have run the program with different numbers of rays of the diffuse bulb and different numbers of points in those that the surface are divided, to see the evolution of the values that we obtained, using the program, for the different form factors, and how accurate are they in comparison with the analytic solution.

As an example, the obtained results for the form factor between the vertical surfaces are shown in Fig. 9.

In the case of the form factor surface–surface we can observe that, excepting the calculations with one point on the surface, with a low number of rays we obtain results close to the analytic solution.

The results obtained with the program are satisfactory, since; the reached values are, on one hand, very next to the values calculated analytically and on the

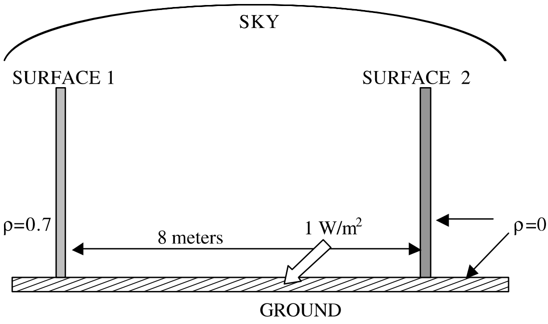
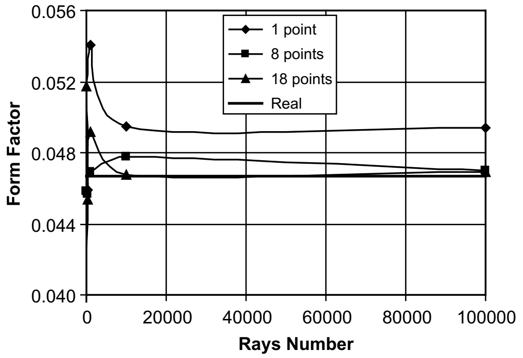


Fig. 8. Scheme of the validation case #1.

Table 1
Analytic solution (validation case #1)

$\mathrm{FF}_{\mathrm{surface-surface}}$	$\mathrm{FF}_{\mathrm{surface-sky}}$ (diffuse radiation)	Reflected diffuse radiation
0.047	0.477	0.096



		Rays number of the diffuse bulb				
		100	**500**	**1000**	**10000**	**100000**
Number of points	**1**	0.040	0.046	0.054	0.049	0.049
	8	0.046	0.046	0.047	0.048	0.047
	18	0.052	0.045	0.049	0.047	0.047
	Real	0.047				

Fig. 9. Comparison between the methodology results and the analytic solution. Validation case #1.

other hand, it is observed that when increasing the number of rays for bulb (or the number of points) the accuracy is increased.

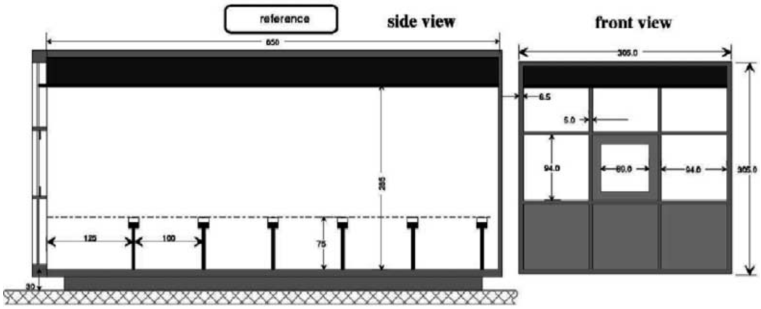
8.2. Validation through experiments

Validations of all the radiation components have to be done using experiment results. With this purpose, we have used an experiment focused on the calculation of daylight inside a room, and for this reason an easy adaptation of the implemented software has been necessary for its used in indoor spaces.

We have selected a new and well recognised experiment for the calculation of the luminance levels in a room. The experiment was carried out in a room situated in Switzerland (latitude 47° N). (Michel and Scartezzini, 2003). The room had only a glazed surface, and it was facing south.

A geometric description of the room and the optical properties of the surfaces are shown in Fig. 10.

The value of the parameters required to run the program have been chosen looking for a good level of precision and low time of execution, they are shown in Table 2.



Lateral surfaces reflectivity	0.81	Nearby ground reflectivity	0.38
Back surface reflectivity	0.73	Distant ground reflectivity	0.06 - 0.10
Roof reflectivity	0.81	Double glazing transmittance	0.8
Interior ground reflectivity	0.16		

Fig. 10. Scheme of the validation case #2.

Table 2
Chosen program parameters (validation case #2)

Number of rays of beam radiation	216
Number of dimensional altitudes	24
Number of rays of diffuse radiation	1000
Number of rays of reflected diffuse radiation	25
Number of reflections allowed	2
Number of points	1

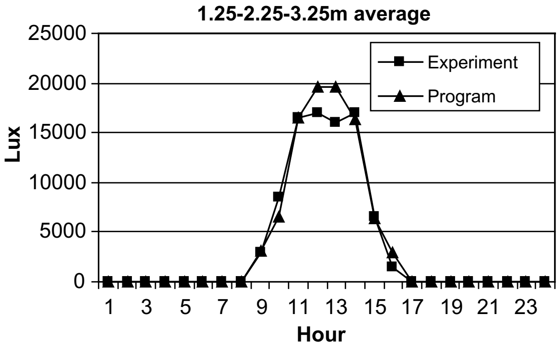


Fig. 11. Comparison between the methodology results and the experiment results. Validation case #2.

The points, in which the measurements and the calculations were realized, were located at 1.25, 2.25, 3.25, 4.25, 5.25, and 6.25 m from the window. The comparison between experiment results and the values calculated with the program are shown in Fig. 11. This figure represents the average values for the three first points.

Asymmetric values in the experiment results make us think that the day of the experiments it was not at totally clear sky conditions. This can be clearly seen at hours in which the maximum occurs; this is, at 12 and 13. But even with all the unknown data related to the experiments, we can asseverate that the model results are quite accurate, and they are in concordance with experiments.

9. Conclusions

The solar radiation is the biggest contributor to the superficial and volumetric energy balances during the daylight hours. In fact, it is the main contributor to the heat gains in buildings, especially residential buildings. It becomes necessary, therefore, in many cases to limit these gains for solar radiation, using elements that shadow the external surfaces of the buildings, resulting in improvement of the interior comfort, and to a reduction of the air conditioning costs.

The methodology has been described for the treatment of the exchanges of heat by radiation in enclosures, closed or opened. This methodology is based on a method of characterization, and it has been developed and implemented in a software tool for the doctoral thesis of the author (Sánchez, 2003). The main reason to use an indirect method, like a method of characterization, instead of a direct method, is that inside an urban environment, the number of surfaces that can block or reflect the solar radiation toward the building is enormous. This way, keeping in mind the relative importance of the solar radiation over other heat fluxes, a good calculation method for the direct, diffuse and reflected components is necessary. The proposed methodology contemplates the complete process, beginning with how to characterize surfaces and volumes, and finishing with the calculation of all the components of the incident solar radiation on an external surface.

The quantitative characterization of the phenomenon has been carried out on a real case, and a new and easy to understand concept has been defined: the modified albedo. With the help of this parameter it has been possible to compare the solution given by a simplified model, and the one obtained from the proposed methodology.

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