A DAYLIGHT SIMULATION TOOL INCLUDING TRANSMITTED DIRECT AND DIFFUSE LIGHT

Application to the evaluation of daylighting inside glazed intermediate spaces

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ABSTRACT

The paper describes new improvements in SOLENE, a set of numerical models for the simulation of natural light in both the urban morphologies and the indoor architectural spaces which is developed in our laboratory. This tool takes into account the direct solar and the diffuse sky luminous energies for the evaluation of luminance, that can be computed on the real surfaces of the environment (ground, walls), or on a false working plane. The tool allows the computation of some classical parameters (daylight factor), but makes it possible to get other informative descriptors.
After a brief presentation of the tool and its general features, we will specially focus on the model of the physical behaviour of light and our original way to manage with multiple transparencies. This last makes it possible to take into account some complex cases : intermediates spaces (atriums, covered galleries, glazed corridors), multi-layered fenestration systems, or semi-transparent screens (vegetation).

INTRODUCTION

The last few years experienced a growing increase in the need of accurate simulation and analysis tools for daylighting ; they may concern both visual and thermal comfort, as well as energy savings.
But most of the existing tools suffer from some disadvantages, as restrictive conditions about the input geometry (rectangular shapes, single window), limited sky conditions (CIE[1] normalized skies), and a reduced field of investigation due to a separate approach for indoor and outdoor spaces. Generally indoor spaces are completely disconnected from the outdoor environmental conditions, and the evaluation of indoor illuminance is carried out in two stages : firstly to collect sky illuminances on the interface (the window plane), secondly to regard transparent areas as new diffuse light sources for the interior spaces. Unfortunately the average conditions which were evaluated on the glazing do not take into account the morphology of outdoor surroundings (geometry of obstructions, reflectance of the surfaces).
So except for learning purposes, the constraints above are too restrictive to allow realistic simulations. Despite the numerous methods that have been developed for basic cases, the lack of simulation tools for the analysis of complex environments (morphology, materials and sky exposure) remains obvious, when more accuracy can lead to a better understanding of the potential links between the morphological descriptors and the resulting environmental characteristics.
It is the reason why the CERMA is involved in the development of high-performance simulation tools ; one of these tools is SOLENE, allowing no particular restriction about the geometry, none about shape, size and type of glazing. As a result the software works as well for large scaled urban morphologies as for interior architectures.

THE SIMULATION PROCESS

The whole process can be split in two main steps : First step consists in gathering luminous energy from both the sun and the sky vault ; the second one in analysing the physical behaviour of light when hitting a plane surface (obviously dependent of its material), in order to start a multi-reflection process.

Sun and sky modelling

Sun is modelled as a spherical point source ; its position is driven by the celestial geometry (see Fig.1) and its energy is given by a statistical radiance model (which depends on many parameters, such as the solar constant, the solar altitude, excentricity, air mass, turbidity, etc.)

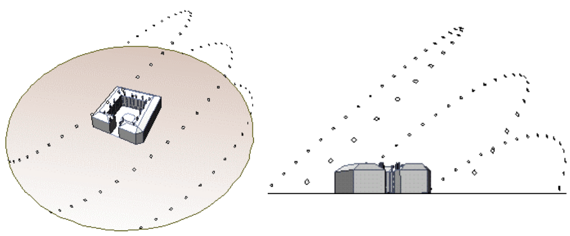


Fig. 1. Sun paths over a urban scene at equinox and solstices (1/2 hour steps).

[1] Commission Internationale de l'Éclairage.

The sky vault is considered as a hemisphere of infinite radius, with the scene to be simulated located at its centre. This hemisphere is meshed with a geodesic triangulation of 4^n elements (most of the time the subdivision in 1024 elements is a good compromise between precision and speed). Finally the sky vault can be seen as a source of diffuse energy with a non-uniform luminance distribution. The luminance values are numerically described by the well-known and robust "all weather" Perez model [7] ; for normative purposes the conventional CIE overcast and clear skies have been implemented also in SOLENE (the parameters of the Perez model do not allow these particular conditions with enough precision). Except for the basic CIE uniform and overcast skies, all the models need as input the angular position of both the sky patch and the sun position, or more exactly the angular distance γ between their direction.
The relative luminance l_v of a sky patch is given by Perez as follows :

$$l_v(\zeta,\gamma) = (1 + a\, e^{b/\cos\zeta})(1 + c\, e^{d\cdot\gamma} + e\cos^2\gamma)$$

with a, b, c, d and e coefficients dependent on the solar zenithal altitude Z and two parameters ε and Δ (brightness and clearness respectively) used to describe the model [7].

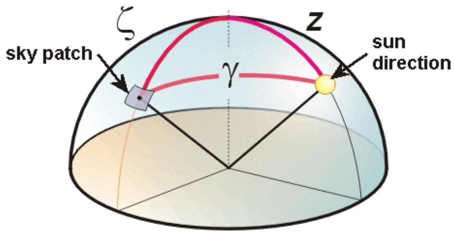


Fig. 2. The 3D geometry and angles required for the computation of the luminance of a sky patch of the zenithal altitude ζ.

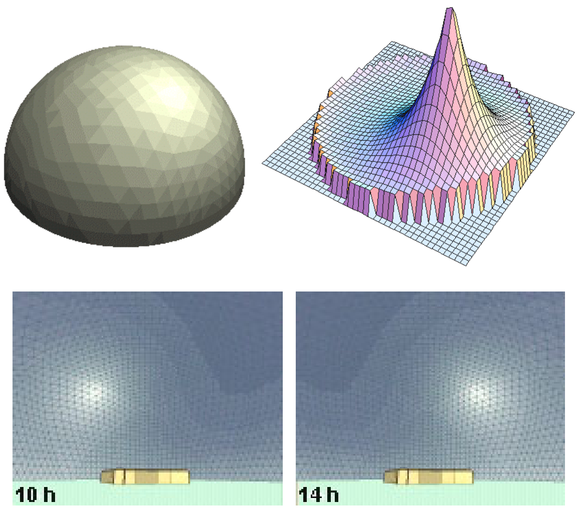


Fig. 3. Visualisation in SOLENE of the luminance distribution for a clear sky on the meshed hemisphere (1024 patches) ; each triangle is coloured according to its luminance value (*top left*). An alternate representation mode of the same sky with height fields (*top right*). Under the sky vault : two pictures of a one-hour step animation showing the displacement of the area of high luminance levels (*bottom*).

The geodesic triangulation of the hemisphere used for the computation of the contribution of the sky vault (see below) enables also good conditions for visualisation (static or animated pictures), assuming a single luminance value over each triangular patch.

Illuminance of the environment

The illuminance level has to be evaluated for every point P of the studied scene ; it consists in collecting radiance or luminance from every visible patch of the sky vault. As a result it theoretically needs a double integration over the whole hemisphere :

$$E_P = \int_{\alpha=0}^{2\pi}\int_{\theta=0}^{\pi/2} L(\alpha,\theta)\cdot\cos\theta\cdot\cos\eta\cdot \mathrm{d}\theta\cdot\mathrm{d}\alpha$$

where $L(\alpha, \theta)$ is the luminance of a point of the sky vault located by its angular coordinates α and θ.
But the obstructions impose to mesh the simulated parts of the 3D environment (Fig. 4) and then calculate the discrete sum that follows for each patch. (SOLENE uses its own algorithm of hidden surfaces removal which is not described here) :

$$E_P = \sum_{i=1}^{n} v_{ij}\cdot\omega_i\cdot L(\alpha_i,\theta_i)\cdot\cos\theta_i\cdot\cos\eta_i$$

where v_{ij} is the visibility ($v_{ij} = 1$ if point P of patch j of the scene "sees" the sky patch i, 0 otherwise), $L(\alpha_i, \theta_i)$ the luminance of the current sky patch i, and ω_i the solid angle under which patch i is seen from P (Fig. 5).

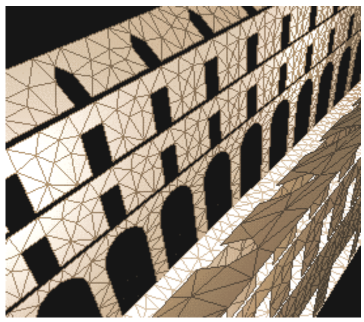


Fig. 4. A meshed urban street ; the size of the patches is adaptable and depends on the expected accuracy and the scale of the simulated environment.

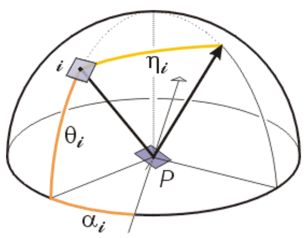


Fig. 5. Required angles to compute the illuminance of the centre P of a scene patch, collected from a sky patch i. α_i and θ_i are the azimuth and altitude of the sky patch i respectively, and η_i the angle between the sky patch and the normal to the surface element of the scene containing point P (this angle is measured on a great circle of the hemisphere).

The task is performed independently for the direct illuminance levels (sun) and for the diffuse ones (sky vault). Then these results make it possible to get the illuminance level for every patch of the meshed scene, due to the fact that these quantities are additive, as shown in Fig. 6.

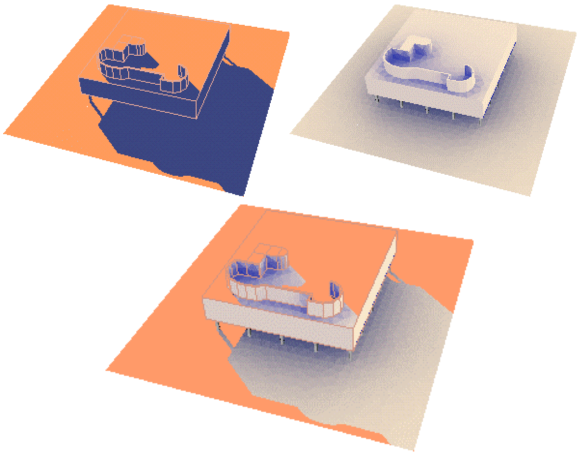


Fig. 6. A simulation of the Villa Savoye in SOLENE (sept. 21st, 10 h, clear sky) : The direct illuminance levels (*top left*) ; the illuminance levels due to the sky vault only (*top right*) ; the combination of the previous gives the illuminance levels of the entire meshed scene (*bottom*).

The physical behaviour of light

The previous steps have only solved a small part of the problem since many surfaces don't gather direct luminous energy : they receive only reflected light from other surfaces, according to their reflectivity and relative position ; so the goal is now to model the behaviour of light hitting a surface. Again we will split the problem into two parts : firstly the interaction between an incoming ray of light and the surface of the material, secondly the exchange of luminous energy between the whole of the elements of surface (multiple reflections).

But the complexity of the problem and the great number of parameters brings some necessary simplifying :

- There is no re-emission of light towards the sky (theoretically wrong in case of low cloud ceiling, but according to authors, the error should not overcome a few percents only).
- Emitted or received energy and reflectance are constant over a whole patch (almost true if patches are small enough).
- Every non transparent surface (see below for *Transparencies*) are considered as opaque and Lambertian (ideal diffuse).

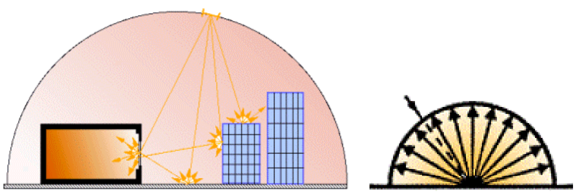


Fig. 7. Reflections on the different surfaces of the urban environment (*left*). Ideal diffuse reflection, which is equal in every direction (*right*).

Light / surface interaction

The above simplifying for opaque surfaces work with most of construction materials. So in the following, the multi-reflection process will use the Lambert law (Fig. 8), where the reflected amount of light is a function of the angle of incidence of the geometrical rays that "carry" the luminous flux. Therefore a given material has one reflectance ρ only.

Fig. 8. Polar diagram of an ideal diffuse patch (Lambert law).

But it is obvious that some new architectural materials don't respect this law ; their reflectivity varies according to the direction of incident rays and observation position. Some of them can be "sharply" directional diffuse (almost specular) and cause glare for certain directions. Our work in the field of luminous comfort often needs more accurate parameters for the definition of the surface properties of the materials than the basic Lambert law. This is precisely the reason why the current developments of SOLENE try to go beyond these restrictions with the implementation of more sophisticated reflection functions (see the section *Future developments*).

Light exchanges between surfaces

The exchanges between surface elements are based on the radiative transfer principles for the heat engineers, which got the name of "radiosity" in the computer graphics community. Briefly the way the exchanges of light take place in the environment depends on the incoming energy and the geometrical relationship between surfaces. The former has been evaluated for every patch in the previous section (*Illuminance of the environment*), and this is precisely this luminous energy that must be distributed over every other patch of the environment (Fig. 10). The radiosity of a given patch is defined as the auto-emitted flux increased by the reflected part of the flux coming from all other surfaces, as shown in Fig. 9.

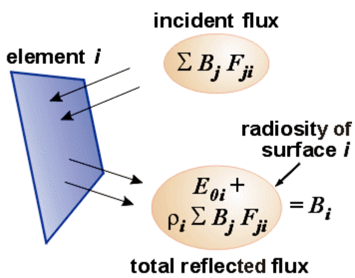


Fig. 9. Diagram of the radiative balance for a patch *i*.

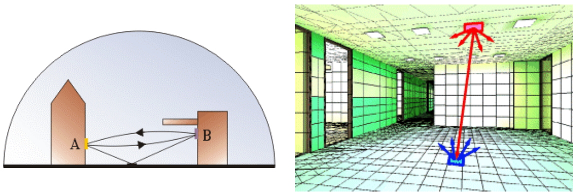


Fig. 10. Light interactions occur outdoor between surface elements of the urban environment (*bottom left*), and indoor (*bottom right*). One patch exchanges luminous energy with every other patch of the scene.

For two patches facing together, the proportion of distributed energy is fully dependent (and only) on their relative orientation and distance (Fig. 11, right). This geometrical relationship called "view-factor" or "form-factor" is one of the major task in the calculation process of the radiosities. It is solved in SOLENE with an efficient analytical contour-integration technique [1], which needs to be linked with a hidden surface removal.

Note that the open architecture of the software allows the visualisation of the form factors (in image synthesis they are generally completely hidden in the global radiosity process). One major interest of this visualisation is to display the more "in connection" areas, *i.e.* the areas for which the reflectivity will have a great influence on the final illuminances of the whole simulated environment (for example it can point out the zones of which it is necessary to increase the reflectivity to get more light deep in a room, as shown in Fig. 11, left, and Fig. 12).

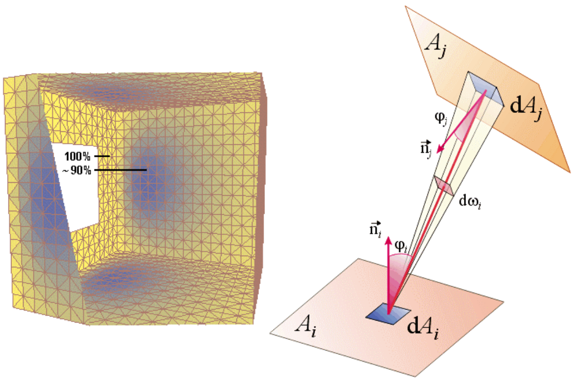


Fig. 11. The open architecture of SOLENE allows the visualisation of the form factors values (*left*). The geometry of form factors between two elements of surface (*right*).

Then the radiosity solution itself is calculated by the well-known and efficient "progressive refinement" iterative method due to Cohen [6], providing as a result the radiosity of every patch of the simulated scene (it gives in the same time the transmitted and absorbed energies – useful for a heat transfer model). So the multi-reflection method enables us to evaluate illuminances of which the major part (or even the whole) comes from the light reflected by the other surfaces.

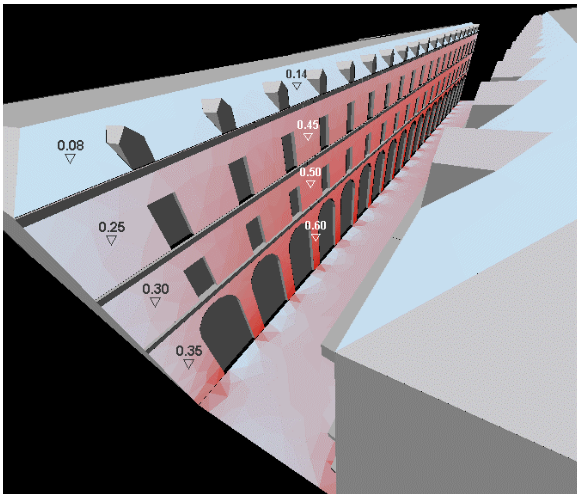


Fig. 12. The visualisation of the form factors in a urban street, displaying the importance of the middle area of the façades in the multi-reflexion process.

This phenomena is particularly important in case of "intermediate" spaces, since they generally try to bring as much light as possible in dark areas (bottom of deep atriums for example), or to areas that do not see the slightest part of the sky vault (as the street shown in Fig. 13). But most of these intermediate spaces are separated from the outer surroundings by vertical or horizontal/sloping glazing. Therefore to want to estimate luminance levels in intermediate or indoor spaces imply that the processing of the transparencies is completed with enough accuracy. This topic is developed in the next section.

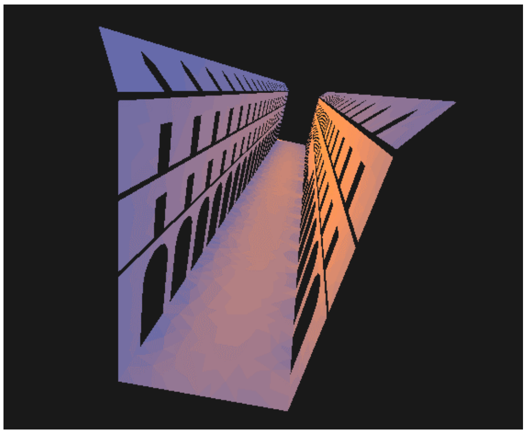


Fig. 13. Cartography of the contribution of the multi-reflexion process in the same street (difference between the illuminance levels after and before the process ; the luminance values are read in databases that are generated by the simulations and linked to the geometry file).

TRANSPARENCIES

As already said in the *Introduction*, the problem of glazing is generally solved by considering them as new diffuse light sources. But this simplistic approach is not able to give an account of a dissymmetry in the external masks or in the distribution of the sky luminances, since they are averaged on the whole window plane.

Transparencies in SOLENE

In SOLENE a window plane is considered just as a "normal" element of the geometry, however with some additional properties. For a specific patch of the 3D model, the status of "opaque" or "completely transparent" (*i.e.* a hole) is given by the orientation of the patch normal line.

Referring to the left picture of Fig. 14 we notice that the outer and interior walls are opaque to rays coming from the sky vault (opposite normal lines), while the glazing becomes "transparent" with a transmission factor ρ_1 (normal lines in the same half-plane). This factor is theoretically dependent of the incidence angle of the incoming rays, but most of time we keep it constant since the variation is not really significant as far as 60° of incidence (it is taken into account only for specific problems, through its law of variation and the incidence angle of the incoming rays). Right picture of Fig.14 shows something similar but now it is the light reflected by an interior patch in question : all the walls remain opaque while the glazing normal line has to be reversed to give it a transparent status (with a transmission factor ρ_2, different from ρ_1 if needed).

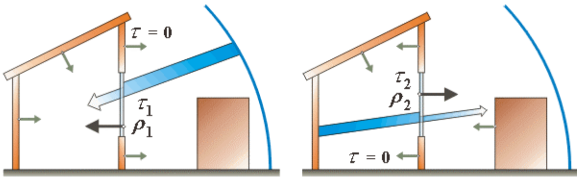


Fig. 14. Glazing is considered as an "ordinary" patch, but with an unsettled normal : it changes according to the direction of crossing.

Practically the problem is solved in SOLENE by separating the two sides of the glazing ; it consists in two merging planes, each of them with its own characteristics of transmission and normal line. The algorithm uses the appropriate one on condition that it knows whether it's a glazing or not ; this information is numerically provided in a specific file linked to the geometry file.

This principle allows multi-reflections through complex or/and multi-layered glazing, as well as other applications mentioned in *Future developments*. Its most important power is that it does not enforce the slightest limitation about the number of apertures (a ray of light can go across several windows), their position (vertical, horizontal, sloping), or their shape (a window patch is just like any other opaque patch).

A CASE STUDY

As an example we have chosen a study in a complex building not far from Paris. This is an extension of a large hospital, well-lit on the second floor by four long zenithal apertures ; this level for reception and consultations has three glazed waiting rooms (Fig. 18). The first floor is a patio surrounded with laboratories. The problem is to bring enough natural light to the laboratories without too much direct sun lighting for the waiting rooms. The study has been completed in two phases, with a necessary modification of the size of the zenithal apertures as a conclusion of the first one. The second phase has consisted in checking the illuminance levels in the laboratories for two different layouts : without and with transparent dividing walls between the laboratories.

The following false-color pictures exhibit some of the features of SOLENE and end with the particular management of the transparencies.

First picture (Fig. 15) is the result of a simulation that consider the direct sunlight only. It shows the duration of sunshine over one specific day (march 21st) by one hour steps.

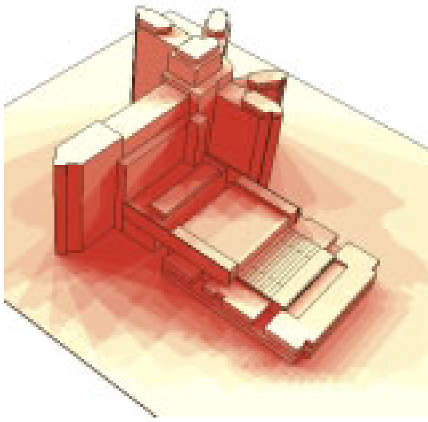


Fig. 15. Simulation of the duration of sunshine at equinoxes for the whole complex.

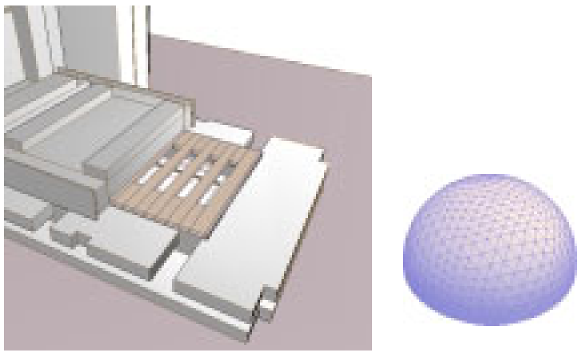


Fig. 16. The part with zenithal openings which has to be studied (*left*). In the following we consider an overcast sky (*right*).

The sky vault only is now taken into account (simulation with an overcast sky). Simulation shows that the illuminance levels are important on the second floor (reception and consultation), the maximum value reaching 3000 lux near the waiting rooms (Fig. 17). This conclusion has lead to a reduction of the size of the apertures, mainly for over-heating problems.

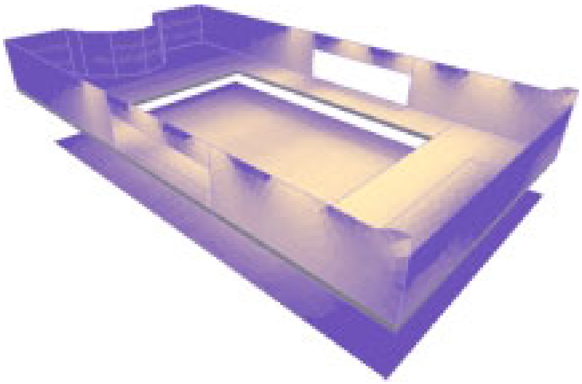


Fig. 17. The illuminance levels of the second floor show high values (around 3000 lux) near the waiting rooms.

Some changes both in the size and the position of the zenithal glazing have permit to reduce the illuminance levels onto the reception floor and patio, as shown in Fig. 18.

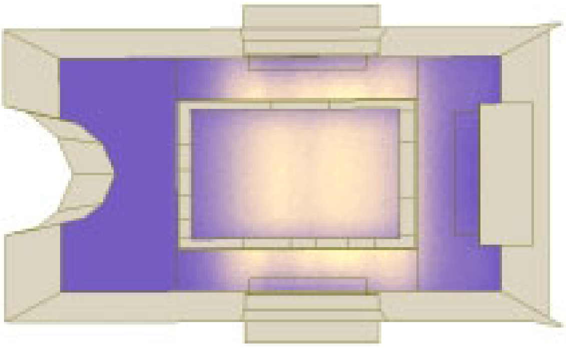


Fig. 18. Illuminance levels of the patio with an overcast sky after modification (this picture shows clearly the three waiting rooms).

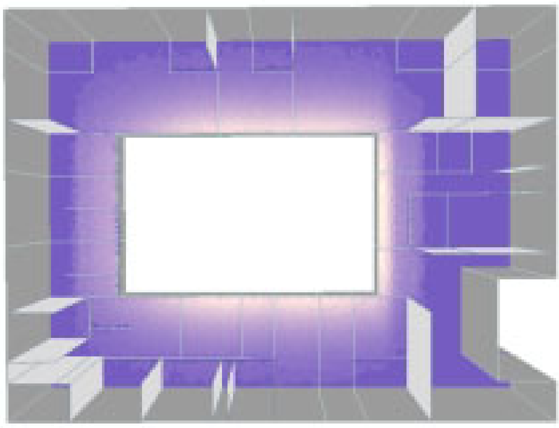


Fig. 19. Illuminance levels with an overcast sky on a 0.8 meter high working plane (our attention is now focused on the laboratories, so the patio is neither displayed on this picture nor on the following ones).

Next picture (Fig. 20) displays the benefit due to transparent dividing walls between the laboratories. Maximum benefit is around 290 lux, which is quite important. It shows also that this benefit is not spread equally depending on the direction ; the above value is obtained by the glazed walls, in a parallel to the zenithal band windows.

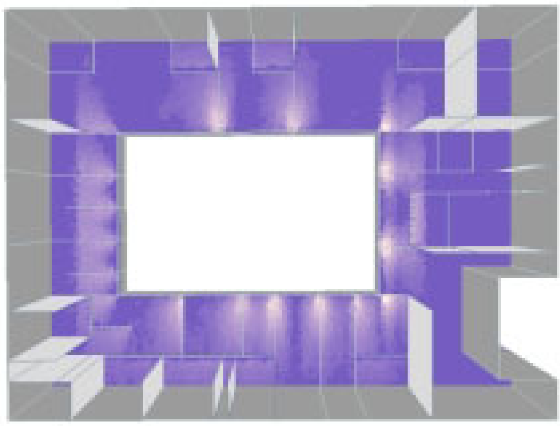


Fig. 20. The illuminance benefit due to glazed dividing walls.

We think very important to return the results of the simulation with intelligibility. It is why great effort has been made for the visualisation module. It allows good flexibility on the range of false colors, the geometry and the data to be displayed, etc. Fig. 21 below exhibits an example of a reduced range of display : the areas getting more than 200 lux only with the previous sky conditions.

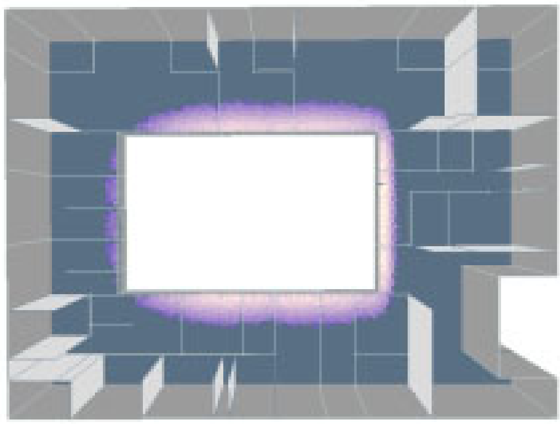


Fig. 21. Areas with more than 200 lux.

This example shows clearly that the resort to simulation tools can bring essential informations to the architect. But complex geometries cannot be satisfied with simple evaluation tools that impose too many restrictive conditions for use. SOLENE can overtake these restrictions, since it does not impose particular conditions on the geometrical data.
The software gives also access to other kind of information, such as the daylight factor on a fictitious working plane, or the areas of visible sky from a particular point of the environment (Fig. 22) ; it is well known that some important psycho-physiological comfort problems can be generated if there are no possibilities of change in the focusing distance of the eye (alternate between close and far focusing).

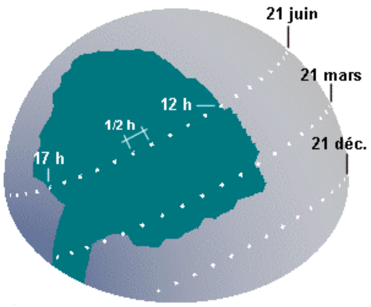


Fig. 22. Example of the sky area seen through a window, with superimposition of the solar paths.

FUTURE DEVELOPMENTS

As said before, the current goal is to implement bidirectional reflection functions (BRDF) linked to a material database. These functions allow to consider other types of reflections, from ideal diffuse to ideal specular. We have chosen a database established in 1996 during the CURET program [12] ; the reflectance characteristics of around sixty real and greatly used materials have been measured during this campaign.
Some promising results have already been obtained, but work is still in progress.

Fig. 23. Different types of reflection : ideal diffuse, directional diffuse, rough specular, ideal specular (*from left to right*).

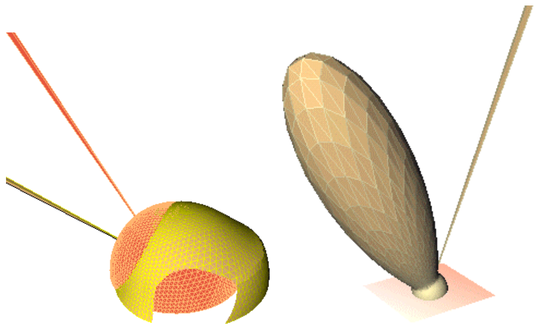
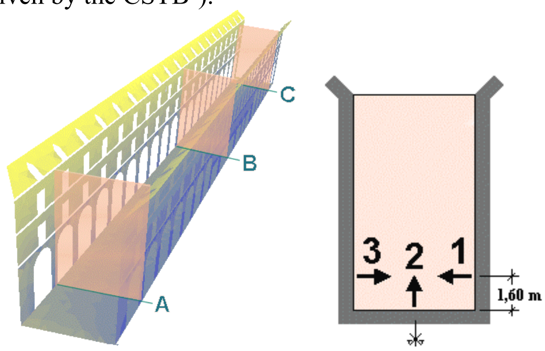


Fig. 24. Visualisation of BRDF with SOLENE : sheet of aluminium for different incidences (35 and 70°) with the Oren-Nayar model of reflectance [5] (*left*), and a polished marble (*right*) with a Cook-Torrance model.

Other working tracks are to put the method used for glazing into practice for semi-transparent screens of vegetation (hedge, row of trees, etc.) ; they can be modeled as a more or less complex geometry to which a transmittance can be assigned ; this one can change with the seasons, in accordance with the species.
Another one – and probably the easiest – is to implement artificial lighting. For that we only need the spectral characteristics of the light sources, that are always provided by the manufacturer ; then a separation of the spectral distribution in a few wavelengths is necessary for numerical calculations. This implementation is planned in the near future.

CONCLUSIONS

We have first discussed the methods generally used for simulation tools in the field of natural lighting. Their lack of precision – or more exactly their ineffectiveness outside very restrictive conditions – have lead us to develop a new simulation tool allowing all types of sky conditions and geometries. Attention has been focused on the different features and the precision. Then we have described briefly the most important principles used in the software, among which models for sun radiance and sky luminance, that build up the input data for a physical model for the luminous exchanges between the surfaces of the 3D geometry. At least we have emphasized the processing of transparencies, that enables to take into account both indoor and outdoor spaces through transparent or semi-transparent media.
This potential and the methods used have brought new directions of investigation, that can be easily included because of the open architecture of the software.
Validation has not been made for the hospital presented in the case study (the project is not yet build), but has been made from measurements completed *in situ*, in particular for the urban street shown on pictures of Fig. 12 and 13. The tables below show a particularly good accuracy between measured and calculated values ; notice that the input values of the sky model have been choosen to equal the luminance level measured in a non obstructed site (given by the CSTB[2]).



		A	B	C
1	measured	5000	4500	6200
	calculated	5000	5200	6500
2	measured	13300	12500	15800
	calculated	13500	13000	15500
3	measured	4900	4600	6200
	calculated	5200	4800	6500

Fig. 25. Comparison between calculated ans measured luminance levels for the urban street displayed on pictures 13 and 14. A, B and C represent the three transversal planes of measurement ; 1, 2 and 3 the position and the orientation of the luxmeter.

[2] The *Centre Scientifique et Technique du Bâtiment* in Nantes can record, among other data, the global and diffuse horizontal illuminances and irradiances.

We will end by specifying that the simulation tool SOLENE works on PC platforms (Windows OS) with OpenGL as visualisation libraries. The user interface is written in Visual C++ and exhibits two main windows, as shown in Fig. 25 : The hierarchical tree structure and the visualisation window with its display context, which allows the user to select the displayed informations.
Even though SOLENE can model very basic geometries (prism, cylinder, etc.), architectural and urban models are generally imported ; the software can convert some major file formats (especially DXF) to its specific data structure.

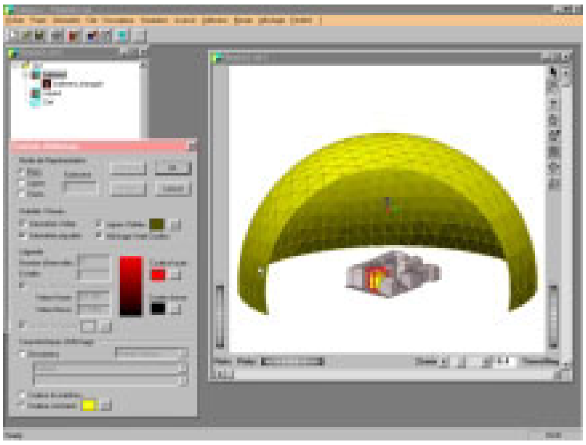


Fig. 26. An example of the SOLENE user interface.

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