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Optimization of daylight in architectural and urban projects

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Abstract

The aim of this communication is to present a formalization of a set of problems involved in the design of buildings or urban settlements with respect to daylight. The complexity of the problem is due to the necessity to take into account the environment of the analyzed objects. Local configuration and presence of other buildings have a strong influence on the possible solutions. They often compel the architect to solve multi scale problems.

For simple evaluations, we developed software able to compute quantities of interest at particular points and for specified periods of time. Because we want these quantities being useful for design, we have to make sure that they correspond to the practices of the architects. Moreover, when the designer is gathering together the relevant information to make the good choices, he has to analyze a lot of configurations and this process can be long and tedious.

So we propose to use optimization in order to provide indications of the best solutions. The first problem is to define an objective function. Usually, it corresponds to the previous quantities of interest, i.e. maximum natural lighting during the whole year but at the same time, a maximum heating in winter and a minimum one in summer. At this point, we yet observe that we have to deal with a multi objective problem. The second point is related to the formulation of the constraints: i.e. area or position of the windows, cost of the devices, limitation of the visual impact, selection of standard devices to modify the illumination, etc… We see now that sometimes we need to solve discrete problems. Finally we have to identify the design parameters that correspond to the input of the above analysis program. Most of these parameters are geometric, but sometimes they are elements of catalogs or they have to obey to norms.

To make sure that this optimization will meet the requirements of the designers, it is necessary to analyze carefully how architects are performing their design and what kind of information they need in order to take the right decisions.

1 Introduction

For about six years, the authors have been developing an educational program called "Heliodon", (Beckers & Masset [1]). The goal was to propose to the architects a program able to help them in the early design of buildings with respect to an optimal use of daylight. This action seems to have been very successful, according to the comments made by more than three hundred postgraduate students performing a master degree in the UPC (Polytechnic University of Catalonia). This tool allows them to test and compare different configurations regarding always three characteristics: interactivity, synthesis and limpidity, (Beckers *et al.* [2]).

Concerning the possible options of a simulation program in architecture, we choose to always work with the complete geometric model, because it is the usual frame of work of the architects. Secondly, in order to obtain high computational performances, we base the calculations on the specific properties of the spherical projection and its representations, (Beckers *et al.* [3]).

However, when the number of situations to be compared becomes important, it is no more possible for the designers to evaluate the whole set of configurations. So, it should be very effective to run optimization programs based on the results obtained by Heliodon in order to select the best solution. Because the architects are not accustomed to formulate this kind of problem, we want to propose here how to proceed.

2 The daylight optimization problem

In the new environmental context, we want to better use the two effects of the solar radiation: light and heat. Note that both have an impact on the energy cost. In both situations, we have to take into account not only the building itself, but also its vicinity that can act as a mask for the radiation process. In practice, the problem is still more complex because of objects interactions; radiation can also be transmitted by refraction or reflection. Today, many programs are able to compute realistic images of a scene taking into account all the luminous effects. The problem is that the designer cannot use this information to modify his design. Because we are interested by the preliminary design, we want to simplify the model in order to make the effects of the design modifications more easily understandable. We are also convinced that a progressive use of the different phenomena will be more efficient in the design process.

The general formulation can be stated as follows: we know the localization of the new building, latitude, longitude and altitude. We also know the topography and the neighborhood. In a first step, we will neglect the atmospheric conditions with the consequence that our study always deals with some kind of ideal or extreme situation: a sunny day or an overcast sky.

With classical algorithms, we are able to describe or evaluate punctual situations either in space or in time. However, to deduce rules helping the user to improve his design, it is often necessary to compute more global results and therefore to perform some integration in space or in time. For time aspect, we need to consider two scales: one related to a day and the other one to a year. But the difficulty is to compare many of these situations. The necessity of navigating in a five dimensions problem - three for space and two for time - is increasing the interest of the optimization.

In this kind of simulation, we introduce the full geometry of the project. Full geometry means that we have not only to describe the exact position and the shape of the analyzed object, but also of all the objects that could hide the sources (Sun and sky). In this way, we are able to compute at any point and at any time the contribution in the radiation process of any element: Sun, sky or other objects. These contributions can vary in magnitude and in nature. Sometimes, we observe directly the solar beam or a beam produced by its reflection; other times we have to deal with diffuse light or its reflection. For interiors, we have also to take into account the properties of the windows. Glasses are producing reflection, refraction and filtering. In a first step of design, we want to avoid giving the properties of materials and to limit ourselves to the pure geometry. In a second step or for improving the behavior of the building, it will be useful to introduce the physical properties of the materials.

3 The frame of the digital mock-up

The gradient based optimization algorithms are suitable to solve pure geometric problems. It is the general situation in shape optimization; see Tortorelli *et al.* [10] or Zhang *et al.* [11]. This situation arises when we want to control only the pure geometric parameters. We need also to compute derivatives or sensitivities. In our problem, it is almost impossible to do that explicitly, but we can achieve this goal using finite differences.

When we have to make a selection between different configurations, like number of windows, etc…, we are in the field of topology optimization. Several techniques are available and investigated mostly in the domain of mechanics, see Bendsoe *et al.* [5], but in architecture we have still to examine how to formulate the different approaches. Today, it seems that zero order algorithms are cost effective for solving our problem, because the evaluation of the functions is not very heavy. If we introduce norms, materials from catalogues, etc…, the only possibility is also to use these zero order methods.

4 The quantities of interest

To perform optimization, we must be able to define three elements. The first one is the objective function; it is the quantity we have to maximize or to minimize. This quantity must be formalized and it is a function of the second elements: the design parameters. In our problem, we decided to use in a first step geometric design parameters because they are the first variables the architect is using to develop his project. Finally, we have also to deal with constraints or restrictions. They express that some design variables or other quantities are bounded. In many problems, we can interchange objective function and constraints.

To manage these functions and parameters, we have first to identify the quantities of interest we are able to calculate. We will consider the following quantities that can be computed at a given point (Puech [9]).

TYPE OF RADIATION	DIFFUSE	DIRECT
3D: radiant or luminous power	Sky factor	Sunbeam energy
Related to a surface, irradiance or illuminance	Sky view factor	Sunbeam energy on the surface
Reflected light	Sky reflection	Sunbeam reflection

Table 1: Quantities of interest

First, we will focus on the first line of table 1. The sky factor is the part of the sky visible from a point; it is measured in percent of the area of the vault of heaven or of the hemisphere limited by the local horizontal plane. This area measured in steradians is equal to 2π sr. Without any mask, we obtain one hundred percent, i.e. on the roof of the highest building in a flat area or on the top of the highest hill or mountain of the considered area. With this quantity, we can find the most opened place inside a given area or volume. To compute averages or to detect a maximum or minimum value, we need to define a grid or a mesh and to eventually perform integration. Building the graph of sky factor on a section of a volume allows finding by simple inspection the point where this function is maximum.

Sometimes, one has to choose the place where the total direct illumination is a maximum. To get this information, we need another kind of evaluation: in a given point, what is the number of hours of direct illumination either during the whole year either in a period of the day during a period of the year? We can achieve this evaluation by using what we call the isochronal diagram. This one is able to give this information in real scale. The two axes of the diagram correspond to hours and days. A horizontal line is describing a day and a vertical one corresponds to an hour along the year. The masks are also projected, so we can directly see without any deformation the time of illumination of this point for all the days of the whole year. Moreover it is possible to take into account the angular elevation of the sunbeam.

This information can be computed at any point of the 3D space and, for example, we can display it on a section of this space. As a consequence, we can also, by simple inspection, identify the best area for the localization of a building or a city. However, here we have maybe to evaluate many sections of the 3D space or to perform the computations on a 3D grid. In this case, the computation is very heavy and time consuming, no longer possible in an interactive process.

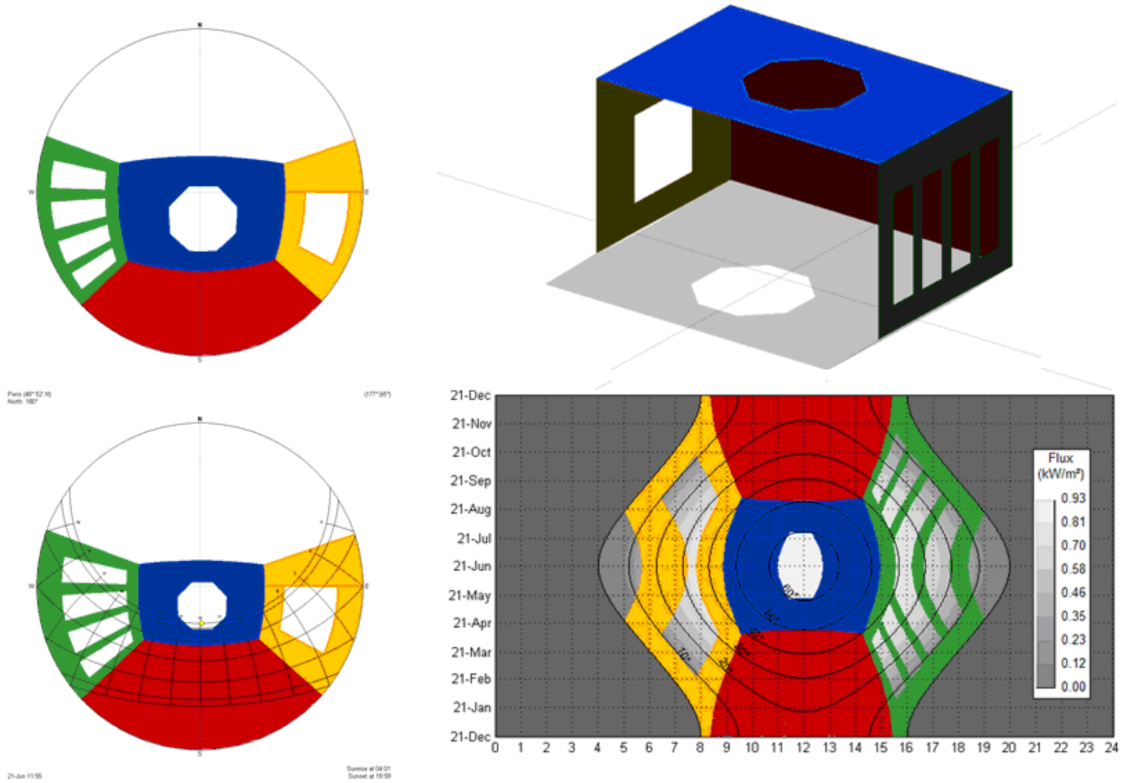

Figure 1: Projections of a simple scene (top right): equivalent (top left), stereographic (bottom left) and isochronal (bottom right)

Focusing our attention on the sky factor and the direct sunbeam, we present two new diagrams derived from the stereographic representation shown at bottom left of Figure 1. This one concentrates all the time information for a given point. For any moment we can know the position of the Sun and its visibility. If we use the equivalent projection of the local hemisphere shown at top left of Figure 1 instead of using its stereographic one, we obtain directly the sky factor without any additional calculation. This one does not depend on time. Using classical z-buffer technique, the computation of these two diagrams is very fast (Beckers *et al.* [3]).

The stereographic projection is giving all the information about illumination, but with a deformation of the time scales. So, it is interesting to use the isochronal representation for showing the sunshine periods over days and year as shown at bottom right of Figure 1. The role of each element of the scene is clearly identified. On the same graph, it is easy to represent the angular elevation of the sunbeam. Taking into account the atmospheric attenuation as explained in Beckers *et al.* [4], we can compute the sunbeam energy. Let us remind that these two quantities: sky factor and sunbeam energy are 3D quantities, i.e., they are not related to any surface.

5 Using the above 3D quantities

To illustrate the background of optimization, we present the study of an apartment situated in a small building surrounded by other constructions in the city of Boulogne-Billancourt, near Paris. Initial data is obtained from geographic records provided by the “Institut Géographique National de France”, [7]. As shown in Figure 1 on the left, the heights are indicated by a color code and specified by numerical values.

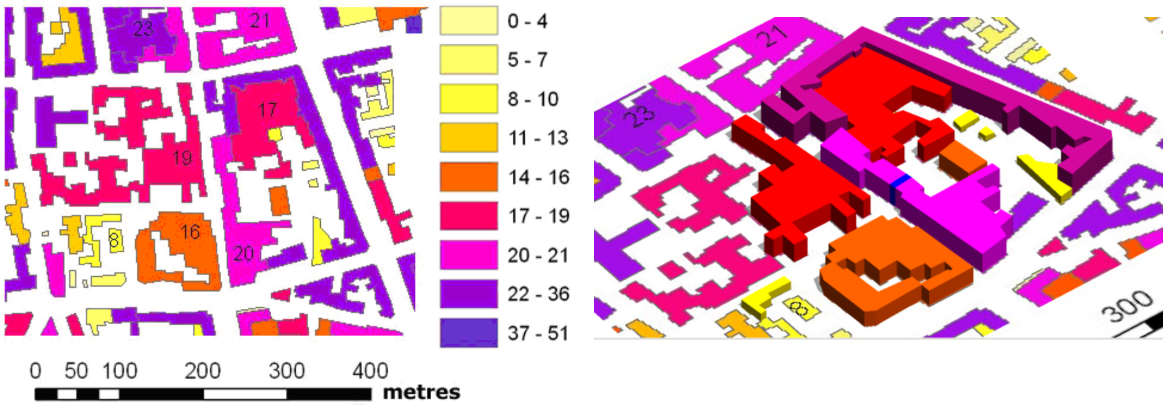

Figure 2: Definition of the urban settlement and 3D model of the analyzed city part

From this map, we define a 3D model with all the buildings that interact with the blue one in the centre of Figure 2 on the right. This one has a frontage on the street in the western direction and another one oriented to east in an interior square.

The problem we want to analyze is the design of two apartments located in this building. We want also to examine if in this situation it is possible to formulate an optimization problem.

As shown in Beckers *et al.* [4], all the results of the subsequent analyses are strongly influenced by the geographic position: latitude and altitude.

In order to perform an optimization, we need first to know the design space. It corresponds to the possible intervals of variation of the parameters we can use in the formulation of the problem. Do we have degrees of freedom to modify our initial project? In this example, we start with a realistic situation that enforces us to check if optimization is possible and to define what kind of optimization should be suitable.

Most studies are limited to isolated houses easy to optimize with very simple criteria. In a dense urban situation, the problem is completely different. As we will see below, we can have places where Sun is never entering in winter; hence optimization criteria must be very flexible in order to address the real situations encountered in cities. Let remind that today most people are living in cities and that some efforts are made to concentrate the populations.

It has also been experimented in other disciplines that when a method of optimization is mature it is not straightforward to convince the professionals of the domain to use it, because they need to perceive the practical advantages provided by the new method.

In a too constrained situation or if the problem is not properly formulated, it can occur that the design space does not exist. So, the first task of the designer who wants to perform an optimization is to define where he can improve his project and what the degrees of freedom are. Secondly, he has to formulate the restrictions or the bounds that affect the design parameters. And finally, he has to check if they influence the objective function.

In an urban configuration, we observe that many conditions are fixed *a priori* and we will see in this example that we have not so many possibilities of improving the project. We have to choose carefully the level concerned by the optimization: city, small group of buildings, single building or apartment. However, if we choose to work at a local level, the boundary conditions have to be defined in the global model.

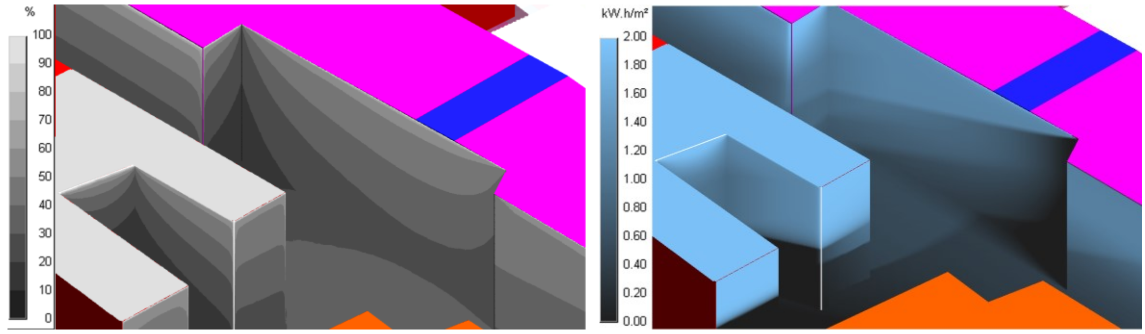

Figure 3: Analysis of the sky factor on the western side of the building (on the left) and energy carried on by the direct solar beam in the winter solstice, December 21 (on the right)

Let us now examine the western frontage as shown in Figure 3. The bottom-top sky factors vary approximately from 15 to 80%. The sky is strongly visible at any level, because the street is opened on a square in front of the building. However, as the frontage is west oriented, we will verify that sun-path obstruction will be very important.

On December 21, sunshine is weak because the masks are very effective (Figure 3 on the right). On June 21, it is the opposite: the left part is more occulted, but sunshine is generally much higher (Figure 4).

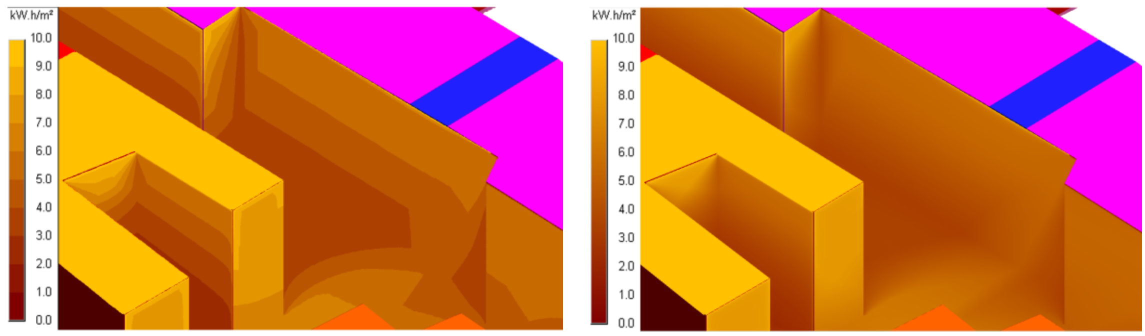

Figure 4: Energy carried on by direct solar beam in the summer solstice, June 21, discrete coloring (on the left) and continuous one (on the right)

We can obtain precise data of sunlight or skylight on any plane of the scene. This could allow us to locate the maximum of the radiation in each season or to determine the impact of any edification on the radiation received by the others. So, we could optimize the location, extension and orientation for solar cells using techniques of layout problems as proposed by Cagan *et al*. [6] or geometry and transparencies of a new building that would not impact too negatively on solar lighting and heating of the preexistent ones. Another problem is the placement of a new building in an urban environment; it is very similar to that presented by Pál [8].

Natural illumination is a multi-scale problem: it concerns urban geometry, architectural decisions and interiors design. So, optimization should deal with general urban modifications, with the shape of some edifices and their windows or with the inner separations in a room…

We want now to analyze an apartment situated on the ground floor as shown in Figure 5. This space is six meters wide and very deep. On the western frontage, there is a window filling entirely the wall; on the eastern frontage, we imagine three traditional windows (1.2 m. x 1 m.).

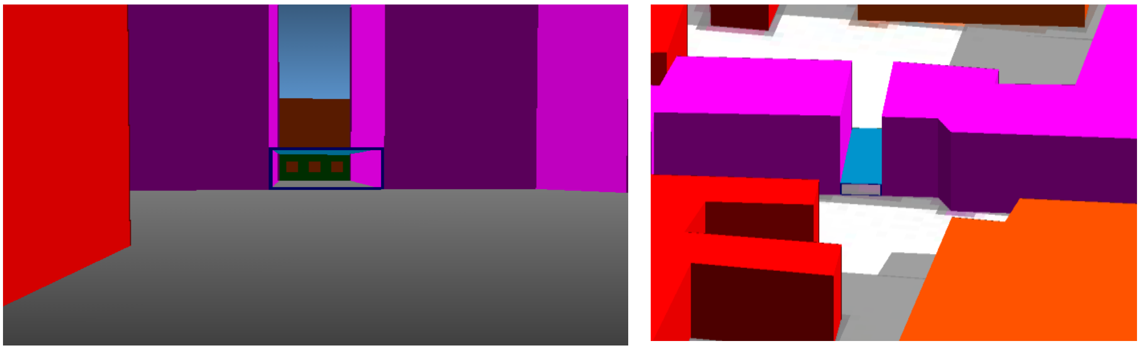

Figure 5: Selection of an apartment in the ground floor of the building

As shown in Figure 6, when positioned in the west side of the apartment, we receive Sun during up to three consecutive hours at the equinox, but never in winter. The influence of the western window is perceived at the other extremity of the room where sunlight is received for short time on equinox and summer sunset. However, the three eastern windows are providing very few morning sunlight and only in the near space. In the middle of the room, these windows are masked by the building that demarcates the interior square.

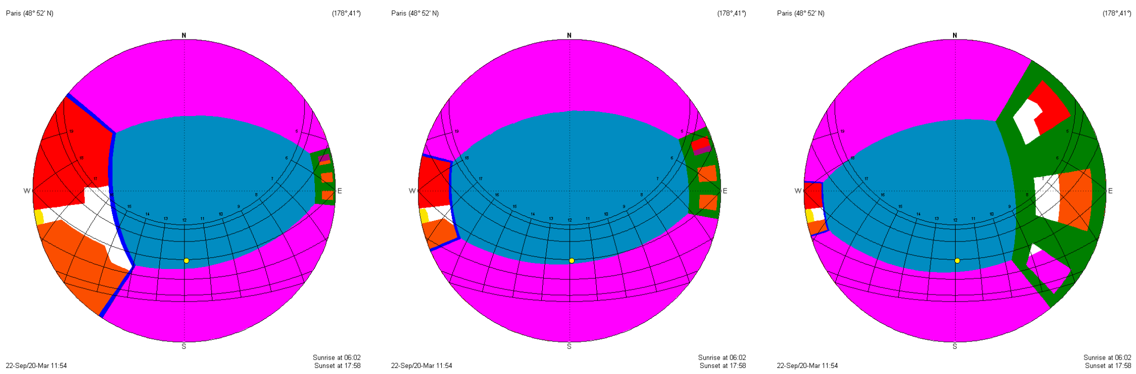

Figure 6: Effects of the windows in three positions: west, center, east

In the isochronal representation of Figure 7, the evaluation of sunlight is easier and more explicit than in the left drawing of Figure 6. Here, time periods are seen in true scale. Moreover it is possible to control in this graph the Sun angular elevation – 30° to 40° in summer – when the beam is reaching the observation point.

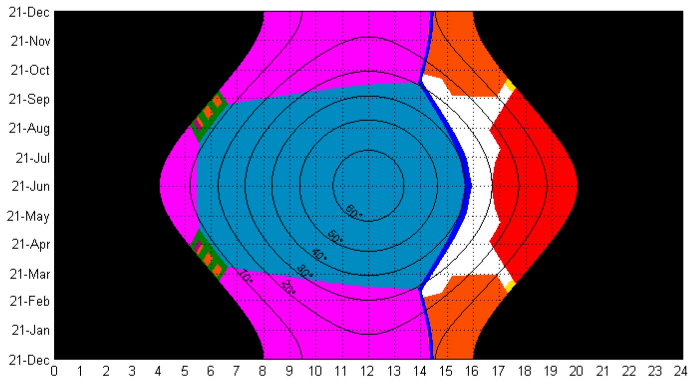

Figure 7: Isochronal representation of the left drawing of Figure 6

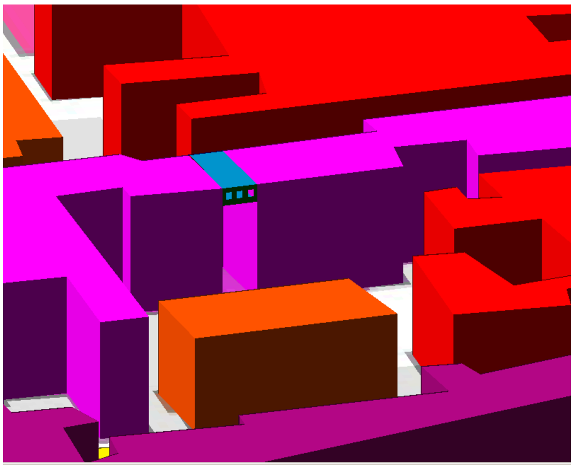

Figure 8: Selection of an apartment in the top floor of the building

Selecting the last floor of the building, as shown in Figure 8, we observe first that the masks are negligible because we are seventeen meters above the street level, in the highest building of the zone.

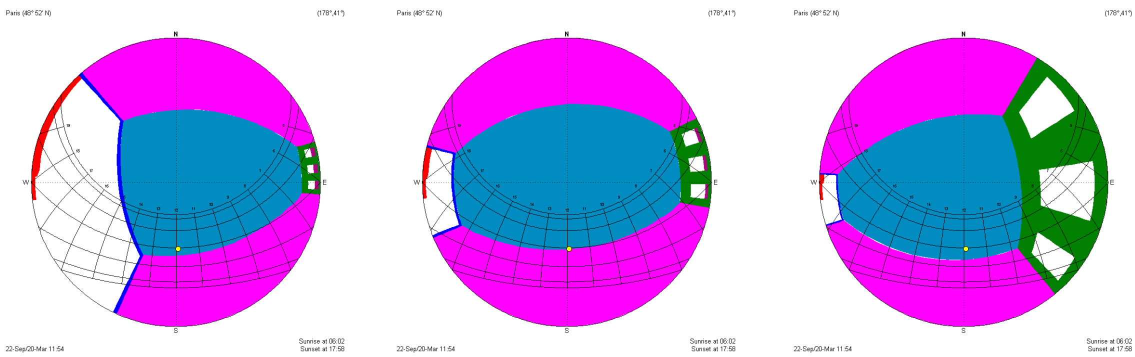

Figure 9: Effects of the windows in three positions: west, center, east, in the top floor apartment

In the western part of the apartment (Figure 9 on left), we receive sunshine during the whole year in the afternoon. In the center, we have more morning sunlight except in winter and in the east part we even receive morning sunlight in winter.

In Figure 10, showing results in summer, equinox and winter, we observe that the room is receiving the maximum sunlight quantity in the equinox period, and this illumination is present everywhere. Note that all the simulations of this paper are performed at eighty centimeters height (workspace level).

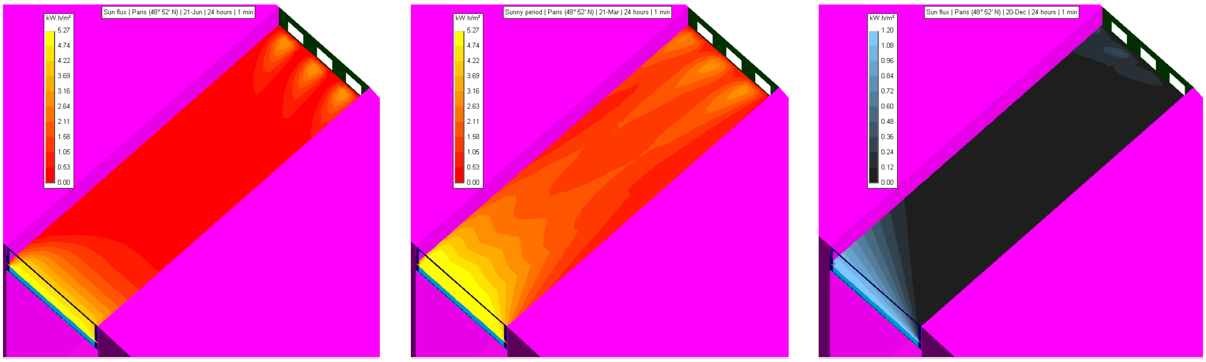

Figure 10: Energy captured in summer, equinox and winter

We selected here a realistic situation, far from optimal. The excess of direct radiation in summer is easy to avoid at the latitude of Paris: a short horizontal protection above the western window would be sufficient. However, sunlight is very weak in winter and there is no way to correct this situation. The sunlight present everywhere in equinox is welcome. The interior separations should be designed in such a way that sufficient interior openings exist or using semi transparent materials. Hopefully, an optimization program will help us to find good solutions. In this local closed area, heating and lighting problems are completely different, because heating aspects are interacting with other physical phenomena such as green house effects due to glazing.

6 Surface related quantities

Coming back to Table 1 (line 2), we see that we can perform another kind of evaluation: the computation of the sky view factor. This quantity is related to a particular surface. If we consider first the diffuse illumination, this view factor enables us to know what quantity of energy or light is transferred from the sky to the analyzed receptor surface.

It is also a first step to solve the radiosity equation. After the development of ray tracing methods, radiosity methods are the last improvements to achieve more realism. However, getting a nice picture of the scene doesn't necessarily help the designer. Solving the radiosity equation is a heavy task, especially if the number of geometric elements that interact is high, i.e., if we consider *n* interacting basic elements, we have to solve a set of n^2 equations.

Considering the impact of direct illumination is also very useful especially for the design of solar cells. It can give us the total energy that could be transformed with a thermal or photovoltaic cell.

The last line of Table 1 concerns the radiation transferred after one single reflection. If we accept a limited discretization of the objects, using the same tools as before, we can increase the realism of the simulation with a reasonable additional cost.

7 Conclusion

The main problem for using optimization in architectural design is to define the relevant quantities of interest. These variables must be meaningful for designers. A second difficulty is to identify an objective function that corresponds to the insight of the architect who wants to improve his design. Depending of the problem we want to solve, we have to select the proper optimization algorithm.

The advantages of the presented methodology are the utilization of specific projections to obtain fast computations and the progressive introduction of complexity to enable the designer to manage all the aspects of the project. We have suggested four possible levels of optimization: distribution and geometry of solar panels, interactions of buildings and their impacts on each other, architectural shape optimization and treatment of interiors. These four situations correspond to the present trend of urban densification. Here we are far from academic optimization problems but with an adequate formulation and efficient evaluation algorithms we are convinced that optimization will improve the illumination quality and the energetic balance of the architectural projects.

References

[1] Beckers B. & Masset L., Heliodon 2, Software and user guide, 2006.
[2] Beckers B., Masset L. & Beckers P., Descriptive Geometry Mutating to Design Tool, In Proceeding of ICCES05 Conference, Chennai, India, December 2005.
[3] Beckers B., Masset L. & Beckers P., Enrichment of the visual experience by a wider choice of projections, In Proc. of the 2007 11th International Conference on Computer Supported Cooperative Work in Design, April 26 - 28, 2007, Melbourne, Australia, Edited by: Weiming Shen & al, IEEE Catalog Number: 07EX1675C, ISBN: 1-4244-0963-2, Library of Congress: 2007920353.
[4] Beckers B., Masset L. & Beckers P., Una proyección sintética para el diseño arquitectónico con la luz del sol, (A synthetic projection for architectural design with solar radiance), In Proceedings of the 8º congreso iberoamericano de ingeniería mecánica, Cusco, ISBN 978-9972-2885-3-1, 23-25 October 2007
[5] Bendsoe MP, Sigmund O. In *Topology optimization: theory, method and application,* Springer, Berlin Heidelberg New York, 2003.
[6] Cagan J, Shimada K, Yin S. A survey of computational approaches to three-dimensional layout problems. In Computer-Aided Design. 34: 597-611, 2002.
[7] Institut Géographique National de France, www.ign.fr
[8] Pál L, A genetic algorithm for the two-dimensional single large object placement problem, In Proceedings of 3rd Romanian-Hungarian Joint Symposium on Applied Computational Intelligence, 2006
[9] Puech C. & Sillion F.X., In Radiosity and Global Illumination, Morgan Kaufmann Publishers, Inc., 1994.
[10] Tortorelli DA, Wang Z (1993) A systematic approach to shape sensitivity analysis, In Int. J. Solids Struct. 30: 1181-1212
[11] Zhang WH, Beckers P, Fleury C., A unified parametric design approach to structural shape optimization, In Int. J. Numer. Meth. Engr. 38: 2283-2292, 1995