Scientific Design of Skylights:
The case of an office building in Gelves, Seville

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ABSTRACT: This paper discusses the effect of a new skylight prototype on the energy and environmental performance of an office building. It has been considered as a priority the study of the factors that relate daylighting and energy, as well as, to a certain extent, other aspects such as ventilation and insulation. Many architectural designs are presented as correct if the thermal requirements alone are met, even at the risk of later energy waste in lighting devices and visual or physical discomfort. On the other hand, large glazed areas allow more daylight into a space, but they may also allow excessive heat gains or losses which increase the air-conditioning cooling or heating load. To avoid these problems, we have considered the combined effect of daylight and energy from the beginning of the skylight design-process. The environmental analysis tool Ecotect has been used together with a daylighting software based on configuration factors that we have used in former PLEA conferences to study the problems of direct sun over architectural structures. This question can not be treated adequately with conventional programs for overcast skies. The skylights have already been constructed and on-site measurements in the offices have been taken to complement the computer simulations data. The results show that it is possible to achieve energy saving and high daylight levels in winter without increasing heat loads during the summer.
Keywords: skylight, daylighting simulation, radiative exchanges, design strategies

INTRODUCTION
One of the main objectives of environmental sciences applied to architecture has been to determine how the built environment is transformed due to the physiognomy of the constructions and how the design should be adjusted to obtain a better climatic performance, in other words, how to optimize the architectural design to obtain a satisfactory and coherent distribution of the natural energy.

To achieve this goal, we think that it is necessary to relate energy use and luminous efficacy during the design-process [1]. In this regard, previous works have stated that a correct design of glazed surfaces in the buildings envelope, in which thermal aspects and lighting are both considered, can considerably reduce the energy consumptions while contributing to improve the environmental quality of the indoor spaces [2]. Specially in the case of sunny climates, the excess of glazed surfaces must be reviewed carefully to reduce energy consumptions, since they have a very important repercussion in the heating demand [3]. Nevertheless, the energy impact of the design of windows is not being considered by most of architects in the decision-making process.

By the other hand, the problems of direct sun over the architectural structures can not be treated adequately from the illumination point of view with conventional software for overcast sky. A careful understanding of solar geometry for the particular situation is demanded, and then, tools to analyze the paramount contribution of solar gains to the day-lighted interiors [4]. Often the proportion of solar gains in the overall lighting balance is higher than 80% and still it is surprising how few scientific designers are concerned and familiar with sunlight concepts [5].

METHODOLOGY
We have evaluated various skylight models to achieve an optimal design, using the energy simulation tool Ecotect together with a daylighting calculation method that we have used in former PLEA conferences [6,7]. This method, based on the calculation of luminous radiative transfers, represents an advance in relation to the research of J. H. Lambert and his theorem of reciprocity, which was later continued by H. H. Higbie, Yamauchi and Moon among others.

The procedure extends the properties of radiance of diffusing surfaces to luminous exitance of all kinds of building surfaces of whatever shape that are accordingly treated as radiative exchangers by means of the generalized principle of the projected solid angle [8]. One the initial intensity of each surface is known and the primary shape of the exchangers is fixed, successive interchanges can be obtained until a balance of the required accuracy is achieved.

This simulation procedure has the capability to take into account the effect of sunlight both in the radiation quantities and in the illumination field. From the beginning, the daylighting simulation was developed in several phases following the different design possibilities of the new skylights.

DESIGN SCENARIOS

Bearing in mind the aforementioned issues, a new skylight for an office building has been designed in Gelves, town located near Seville. The so-called new "monitors" have been designed to control the incident solar energy in the building through the roof. We should note that this is the surface with the highest incident solar radiation and that it allows the greatest flexibility in connecting offices with the outside environment.

We have evaluated various proposals for skylights in order to determine the forms with better results for a particular situation. The paradoxical question was how to achieve a good day-lighted environment and energy savings in winter without increasing the thermal loads in summer. This question is not an easy one and can not be treated as an isolated factor. We have to take into account that energy savings should not be obtained at the risk of visual discomfort or severe air conditioning loads leading to thermal stress.

Therefore, we analyzed the solar positions of Seville in relation to its climatic parameters. By using the software Ecotect, we studied the ideal orientation and the critical situation of which solar penetration in the offices is not advisable, according to the high probability of clear sky in Seville.

In general terms, the followed procedure of design for the monitors was to open the apertures in the orientations that receive direct sunlight for more hours a day, and to control them by the geometry of the skylights and the design of overhangs. In this regard, we would like to stress that the south is the sole orientation receiving more gains in winter tan in summer in Europe.

Finally, we decided to design conoidal monitors that can be opened with different sections in SE and SW directions. The other surfaces are opaque and insulated to reduce solar radiation. Within the diverse solutions considered, figure 1 shows one of the designs which offer the best estimated performance in terms of energy savings, visual comfort and reduction of thermal loads.

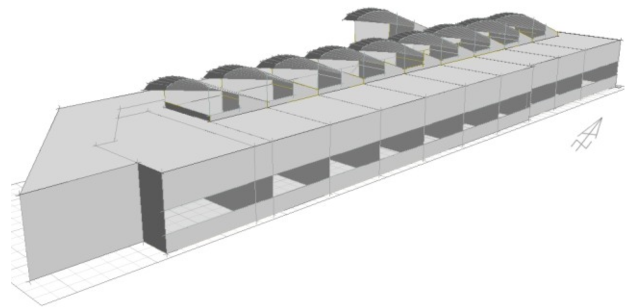

Figure 1: Sketch of the final proposal for skylights.

It was necessary to accurately dimension the monitors to avoid overshadows between them in winter. The aperture oriented SW has been protected by an overhang that avoids the penetration of direct sunlight at times of maximum heat during the summer afternoons. We also took into account the increase of daylighting owing to the reflected solar radiation at the conoidal monitors. Figure 2 shows the penetration of solar radiation into the offices.

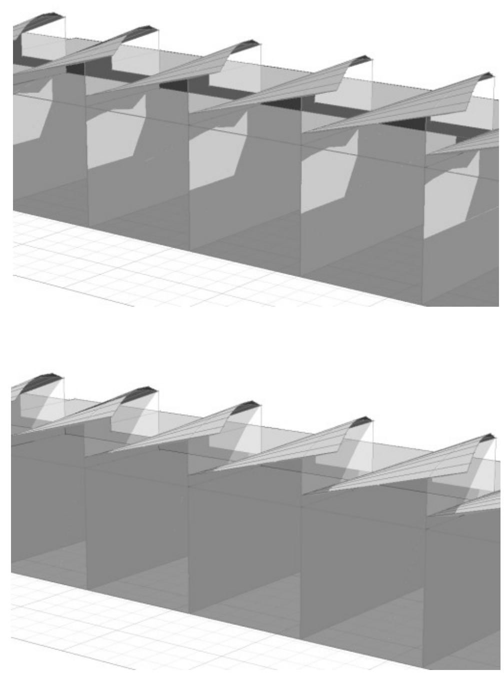

Figure 2: Comparison of the interior shadow range at 12:00 hours in the winter solstice (above) and the summer solstice (below).

The graph below, calculated by Ecotect, shows the annual direct sunlight gains in an office (Fig. 3). As can be seen, we achieved the objective of having more capture of solar energy in winter than in summer.

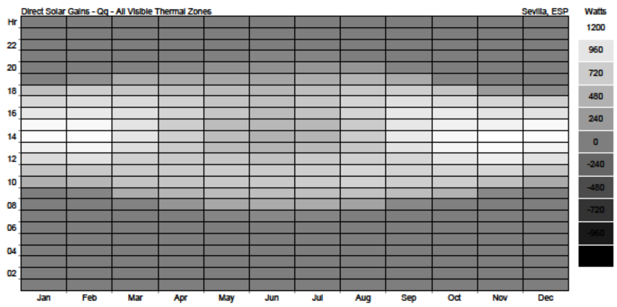

Figure 3: Annual direct solar gains in an office.

The adopted solution not only produces the benefit of having sunlight into the offices when the temperature is below the comfort range, but also considerably increases the daylighting because this radiation is incident on high-reflectance surfaces. This type of solar design in warm climates would not be possible using design methods for overcast sky.

The possibility of natural ventilation was also studied. The monitors have automated ventilation apertures that can be opened at certain levels of temperature and wind speed. They are located on facades with different orientation to facilitate cross ventilation (Fig. 4).

Figure 4: Views of the new skylights.

The entire intervention has been developed at low cost and takes into account the architectural integration of the final proposal.

DAYLIGHTING SIMULATIONS

Two situations have been investigated, overcast conditions (where orientation and hourly and monthly variation) and clear sky with sun conditions (where orientation and hourly/monthly variations are mandatory).

The first condition refers to conventional models for cold and cloudy climates, with limited application to Seville. The second condition is more innovative and typical of warmer regions where some places reach 3.000 sun-hours per year. We need to use it in order to save energy, as the luminous efficacy of free and over-abundant solar radiation is much higher and pleasant than the one registered with artificial luminaires.

Besides, with controlled beam radiation as the main lighting source, we are able not only to produce a more suggestive internal environment, but also to greatly reduce energy-use, especially in air conditioning overheads, as the size of the glazed apertures can be significantly diminished in comparison with conventional skylights [9]. Those skylights did not control radiation and, therefore, they admitted excessive quantities of heat for an equivalent or even lesser luminous effect.

Regarding the simulation that we have developed, the times of the year under study have been the most representative ones, that is, winter and summer solstices and equinoxes. Within each of these days, several hours have been analyzed. Henceforth, a complete knowledge of the performance of daylighting throughout the year is achieved.

METEOROLOGICAL DATA AND COEFFICIENTS

The reflection coefficients of the walls were taken at 0.50 and 0.65 including maintenance, the transmittance considered for the glasses was 0.60 and general cleaning of the offices 0.9.

The climate values have been obtained from a TMY data file for Seville and processed with Ecotect. For daylighting calculation we have used a sky model [10], that defines the vertical illumination (in lux) for clear sky based on the azimuth (ϕ) and the height (θ), by the equation below.

$$Ev = 4000 \times \theta^{1.3} + 12000 \times sen^{0.3}\theta \times cos^{1.3}\theta \times [(2 + cos\Phi) / (3 - cos\Phi)]$$

And in the case of overcast sky, similar to the CIE model, using the following equation.

$$Ev = 8500 \times sen\theta$$

Regarding the possibility of occurrence of overcast or clear sky plus sun we have the following values (Table 1).

Table 1: Probabilities of overcast and clear sky at Seville (Spain).

Type of sky	Clear + sun	Overcast
March/September	76.40%	20.00%
August	86.30%	12.20%
December	78.60%	24.10%

Both probabilities do not add up to 100% provided that there are other types of sky as partly cloudy or average sky.

RESULTS OF THE SIMULATION

We show below some computer results of the simulations (Fig. 5 and 6). Horizontal daylighting values refer to a work plane located 0.6 m above the floor. The sectional views cut across the offices for its center point. Notice that the grid points are taken every 1 meter in the width, length and height axes.

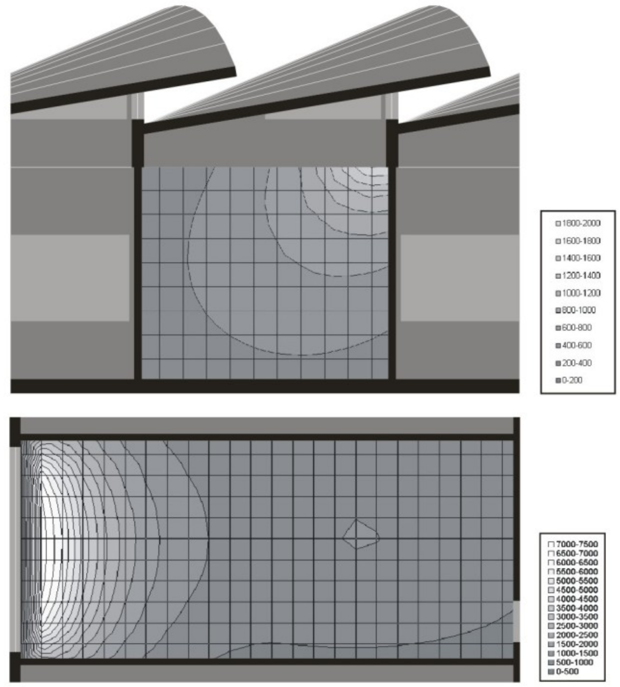

Figure 5: Horizontal and vertical illuminance distribution in an office. June 12:00 hours solar time, clear sky plus sun. Values in lux.

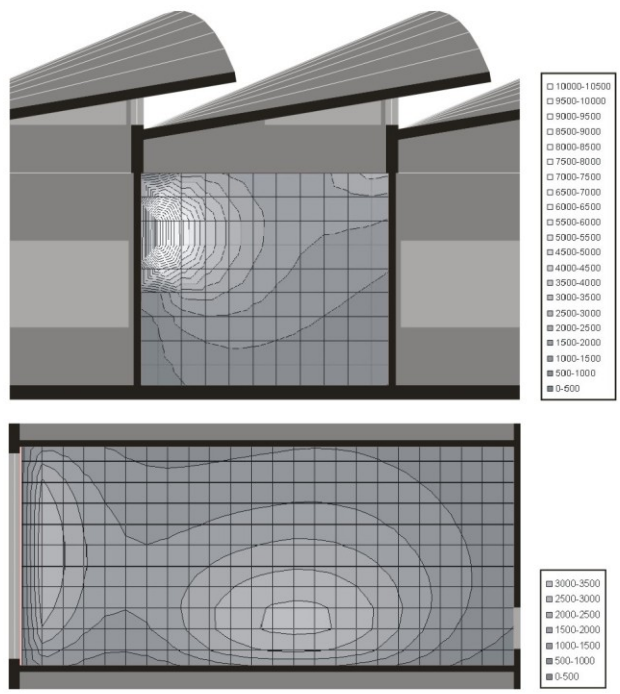

Figure 6: Horizontal and vertical illuminance distribution in an office. December 12:00 hours solar time, clear sky plus sun. Values in lux.

We have to point out that 80% of the studied points showed a level of over 400 lux for all weather conditions and 20% of the points considered were always over 250 lux. In the clear with sun conditions, the daylighting values are higher in the winter solstice than in summer due to the contribution of direct solar radiation to the day-lighted interior.

Daylighting in this new system is greatly dependent on solar illumination and is rarely dependent on overcast or clear sky, and this is in our opinion an important innovation.

THERMAL ANALYSIS

A model was created using the Ecotect software and was applied during the decision-making process to simultaneously analyze the effect of the proposed skylights on the thermal performance and habitability of the offices.

Regarding the materials, the conoidal surfaces were designed with the thermal mass on the inside, because, due to their geometry and orientation, a high solar radiation incidence is expected. After studying various material combinations, we decided to use the following construction system (from inside to outside): 40 mm perforated brick with plaster inside 10 mm, 150 mm concrete, 40 mm extruded polystyrene (XPS), and finally an external self-protected waterproofing sheet. The total U-value is 0.48 W/m2 K and the thermal lag 7.5 hours.

We calculated the effect of the new skylight on the discomfort level (in degree hours) of the offices during working hours, from 8:00 AM to 6:00 PM solar time. Results show that better environmental performance in winter due to the increase of thermal loads can be achieved. During the summer, the control of solar radiation and the possibility of cross ventilation also allow an increase of the comfort level (Fig. 7).

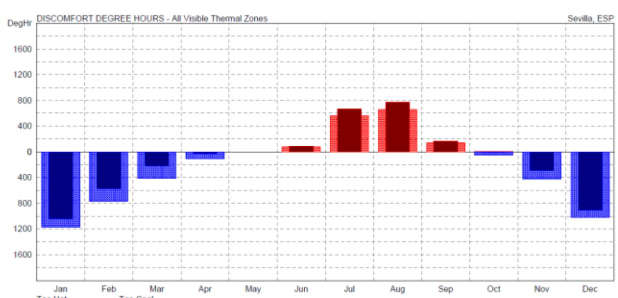

Figure 7: Comparison of the discomfort level in degree hours for an office before the intervention (light) and with the new skylights (dark).

CONCLUSIONS

In general, relatively high and well distributed daylighting levels have been achieved inside the offices. The horizontal dayliging is above 400 lux, with higher values in winter than in summer. The daylighting levels in the vertical planes are significantly lower, which is suitable for office spaces. By the other hand, the new skylights improve the comfort level both in winter and in summer, an improvement which is not obtained at the cost of visual discomfort.

The skylights are currently being monitored. The first data from on-site measurements show that they work properly.

We have to stress that this example and many others that have been built in recent years validate the results of the scientific determinations outlined above. Therefore, they represent an advance in the knowledge of skylights and a clear example of how the prediction of the energy or climate response of architectural structures has become a real possibility.

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