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Solar Radiation in Architectural Projects as a Key Design Factor for the Well-Being of Persons with Alzheimer's Disease

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Abstract: The beneficial effects of solar radiation on human health are well documented. One necessary mechanism triggers the production of vitamin D, whose insufficiency has been linked to a variety of disorders such as diabetes; hypertension; and, more recently, amyloidosis and Alzheimer's disease. However, there are few architectural designs capable of ensuring the adequate provision of solar radiation inside buildings. Conventional fenestration is not sufficient to provide for significant doses of sunlight, even to prevent seasonal affective disorder (SAD). In this paper, we discuss the effect of new design alternatives for skylights, especially in the refurbishment of obsolete facilities. Based on the authors' previous studies, we defined a theoretical model that was subsequently adapted to a real building that was to be retrofitted in an area near Sevilla. After such complex refurbishment was executed, we analyzed the performance of buildings in warm and sunny climates, as is the case of southern Spain, where cloudiness is very scarce and available simulation models are not useful. The study of the factors that relate to sunlight; UV reception and energy; and, to a certain extent, other aspects such as ventilation and insulation has been considered a priority. 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 for more daylight and UV radiation into a space if properly treated, but they may also produce excessive heat gains or losses, which increase the air-conditioning cooling or heating load, respectively. The uncontrolled increase in temperature can have negative effects on the well-being of a person with Alzheimer's dementia. To avoid these problems, we have considered the combined effect of daylight and energy from the beginning of the skylight design-process. Daylighting software, based on configuration factors that we have applied in studies of the complex problem of there being direct sunlight over architectural structures, has been used. This question cannot be treated adequately with conventional programs for overcast skies. The skylights have already been constructed, with special UV increasing glazing and on-site measurements in the offices to complement the computer simulation data. The results show that it is possible to achieve energy saving and high radiation levels in winter without increasing heat loads during the summer. Ventilation is also improved through the aerodynamic design of the clerestories. All this is considered beneficial to improve the condition of users with cognitive diseases as Alzheimer's disease, by virtue of adapted spaces.

Keywords: spaces for Alzheimer's disease; daylighting simulation; radiative exchanges; design strategies; healthy architecture

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1. 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 and fairer climatic performance—in other words, knowing how to optimize the architectural design to attain a satisfactory and coherent distribution of the natural energy. Particularly, daylighting seems to directly affect the behavior of the user suffering from Alzheimer's disease (AD) and its subsequent cerebral processes [1]. Lighting is part of a set of project parameters previously detected as significant due to their impact on the well-being of the person suffering from Alzheimer's disease. The acquisition of sunlight is possibly one of the most influential factors in the design project; it has a direct impact on the patient [2]. The design control of solar radiation sources and their intensity is required at all stages, to achieve the adequate regulation of the daily activities of users with cognitive impairments, such as Alzheimer's disease outpatients [3–5].

To attain this goal, we think that it is necessary to relate energy use and luminous efficacy during the design process [6,7]. In this regard, previous works have stated that the correct design of glazed surfaces in a building's envelope, in which thermal aspects and lighting are both considered, can considerably reduce energy consumption while contributing to the improvement of the environmental quality of the indoor spaces [8]. Especially in the case of sunny climates, such as Southern Spain, the excess of glazed surfaces must be reviewed carefully to reduce energy consumption since they strongly affect the demand for heating [9,10]. Nevertheless, the energy impact of the design of windows is not being considered by most of the architects in the decision-making process because they deal with the minimum performance and not the surplus.

On the other hand, the problem of there being direct sunlight over the architectural structures cannot be treated adequately from the illumination point of view with conventional software for an overcast sky. A careful understanding of solar geometry for the particular situation is demanded; then, tools will be needed to analyze the paramount contribution of solar gains to the day lit interiors [11,12]. Often the proportion of solar gains in the overall lighting balance is higher than 80%; still, it is surprising how few scientific designers are concerned about and familiar with sunlight concepts [13]. The combination of convective and radiative transfers with UV reception is also demanded. The following study has been restricted to architectural spaces without intervention of actual persons, which could be involved in further researches about post-occupancy evaluation.

2. Methodology

The modelling of the characteristic structural, acoustic, and lighting properties of surfaces called conoids has encompassed a significant amount of the career of the authors. Based on this, we can attest to their sustainability and resiliency [14].

From a structural point of view, as ruled surfaces they can be built directly through straight lines (beams or poles); this fact greatly facilitates their construction and scaffolding, as more natural materials such as bricks or bamboo rods can be used without difficulty, even for reinforcement or repair.

Carbon-fiber coating has become a recent alternative for reinforcement, although it is moderately expensive.

The arched section of the conoid, whether circular or elliptic, presents a vertical tangent. Therefore, if adequately constructed it is free from horizontal thrusts that might compromise the supporting frame. In other words, it transmits all the loads of the structure vertically and avoids the use of buttresses.

These consistent and diminishing arches function as girdles for the majority of the surface and provide increased resistance to a significant amount of it. It is true that the calculation of hyper-static arches is not widely treated in the literature, but we suggest the column analogy method proposed by H. Cross [15] as a helpful and programming-friendly procedure.

Due to the curvature of the roof, its aerodynamics are excellent for bearing wind loads and other meteorological phenomena such as rain, drizzle, or snow. At the same time, because of the former, it enhances air flow from the outside or from the internal stack effect with appropriate vents.

Regarding the lighting properties, if, as usual, the glazed apertures lie in the curvilinear extremes of the forms, they bring uniform illuminance as we have calculated and can be easily shaded by eaves protruding from the same brim of the surface.

The acoustic properties stem from the circumstance that the inside surface of the conoid is mostly convex, as we have checked mathematically [16]. The sound waves are diffused in this kind of ceiling, and, consequently, noise and reverberation become dampened. If, through appropriate design, the conoid covers a trapeze or fan-shaped plan, the effect of an even sound pressure is manifest [7]. (In this last case, the surface is not a proper conoid as the forming lines are not all parallel to a common plane).

The aforementioned acoustic benefits are extensive to interior illumination for the same reason: the convexity of forms.

Although strictly speaking not a conoid, because its equation differs from what we have explained above, the cover of a fan-shaped plan with this kind of surface offers a very interesting structural property: the larger spans between pillars are covered by arches, while the tapered end of the trapeze features a common slab or planar beam, which seems very logical from a constructive point of view [7]. In this way, the shells' materials can be lighter and smoother. The result has proven to provide increased insulation and adds a variety of light effects.

Based on the former, we have created different design alternatives in time, to introduce sunlight into the core of buildings that could perform satisfactorily for residential facilities. The main output is based on conoidal shapes. The more evolved alternative for advanced skylights is presented in Figure 1, in which the glazed parts instead of being planar are also conoids. Bearing in mind the problems of heat and light transfer, this feature presents undoubted advantages [16]. Firstly, the glazing is better shaded and protected by the opaque upper surface. Secondly, sunlight and heat transmission are modulated by the smooth curves conjoined to the innovative glass properties. In this way, the glass surface becomes load-bearing and collaborates with the general structure. The form can be easily adapted to arrays of skylights (Figure 2).

The new skylights are more impervious, break-proof, safer, and cleaner in the absence of maintenance because dust collection is diminished with the curvature [16].

In building solutions with a reduced budget, the glazing can be turned into a plane, without severely compromising the performance, as we have shown [17]. These planes are operable to a great extent to increase UV reception when desired and to provide for ventilation.

Regarding sunlight controls in the skylights, we have evaluated various sky models to achieve an optimal design, using a daylighting calculation method that we have developed and applied in previous studies [18,19]. This method, based on the determination of absolute 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 [20], but was insufficiently considered in recent years in favor of indeterminate metrics.

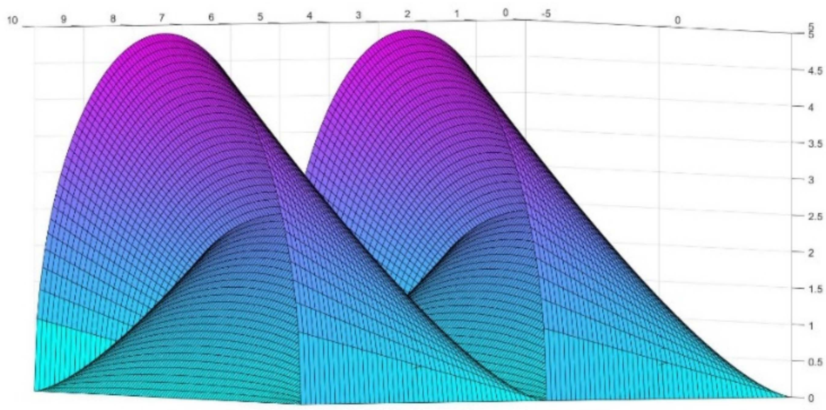


Figure 1. An outline of the proposed skylights with internal conoid glazing.

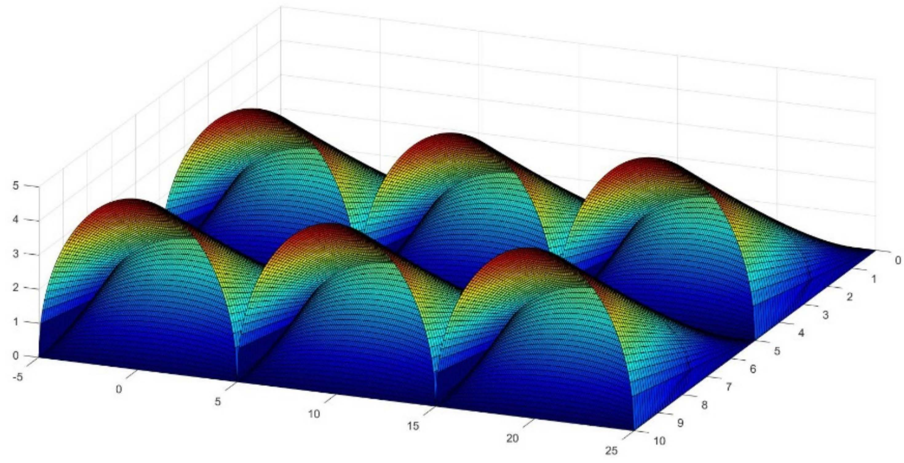


Figure 2. A suggested array of six conoidal skylights.

The procedure extends the properties of the radiance of diffusing surfaces to the luminous exitance of all kinds of building surfaces, of whatever shape, which are accordingly treated as radiative exchangers by means of the generalized principle of the projected solid angle [21]. Once 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 recurrent sunlight (the case of Southern Spain) both in terms of radiation quantities and the illumination field. From the beginning, the daylighting simulation was developed in several phases following the different design possibilities of the new skylights.

Ceramic Materials

The techniques previously described are concomitant with the use of environmentally friendly materials such as ceramics and brick masonry. Ceramics are a natural, lightweight for of insulation known since antiquity. The authors have incorporated this cost-effective material into different projects [16], with positive results in a variety of fields, and especially in the cognitive adaption issue, which is one of the key aspects pursued in the ensuing research (Figure 3). In the case study presented in this article, this solution has been employed.

Figure 3. Vault pieces constructed in hollow thin brick by the authors, in Seville.

3. Design Scenarios in a Practical Case

Bearing in mind the aforementioned issues and the experience gained, a new type of skylight, for a former office building that needed to be converted into residential units, adapted to persons with Alzheimer's disease and other cognitive impairments, 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 for the greatest flexibility in connecting the living rooms 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 use of such dynamic daylighting systems is due to the necessity of providing new sources of radiation for persons suffering from cognitive diseases such as Alzheimer's. Expected advantages are the maintenance of daily circadian rhythms and the avoidance of excessive glare and other stimuli, which could result in the stress augmentation of agitation.

The paradoxical question was how to achieve good day-lit environment and energy savings in winter without increasing the thermal loads in summer. This question is not an easy one to answer and cannot be treated as an isolated factor. We have to take into account the fact 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. We studied the ideal orientation, and the critical situation for 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 via the geometry of the operable 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.

Taking into account this design strategy, we have simulated the effects of various proportions of glazed surfaces in the thermal performance of the offices. We have analyzed the most advisable orientations in this case: SE and SW. The other surfaces have been designed to be opaque and insulated, to reduce solar radiation.

We found that it is advisable to avoid the penetration of direct sunlight at times of maximum heat during the summer afternoons. Therefore, the aperture-oriented SW has been reduced in the W direction and protected by an overhang that increases its dimension in this direction. Regarding the daylighting issues, we simultaneously carried out a pre-dimensioning to check the minimum size of the elements that ensures sufficient daylight.

As previously explained, we have selected conoidal geometries to formalize the design strategy. This geometry allows that the monitors can be designed with different sections in SE and SW directions. Moreover, the obverse of the conoid is convex and therefore can distribute the luminous and acoustic radiative transfers more conveniently.

Within the diverse solutions considered, which include inverted conoidal geometries and various proportions of glass and dimensions of overhangs, Figure 4 shows the designs that offers the best-estimated performance in terms of energy savings, visual comfort, and the reduction of thermal loads.

It was necessary to accurately measure the dimension of the monitors to avoid overshadows between them in winter. We also took into account the increase of daylighting owing to the reflected solar radiation at the conoidal monitors. Figure 5 shows the penetration of solar radiation into the offices.

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

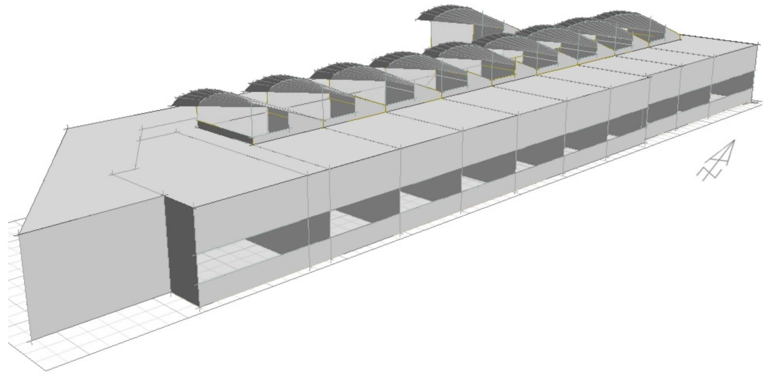
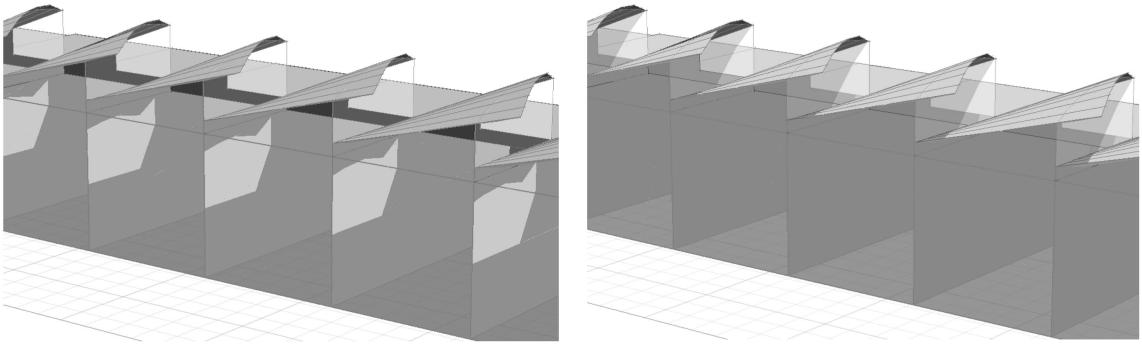


Figure 4. A sketch of the final proposal for skylights.



(a) (b)

Figure 5. A comparison of the interior shadow range at 12:00 h. (**a**) Winter solstice; (**b**) summer solstice.

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. The UVB amount of rays is therefore increased. Such vents are located on facades with different orientations to facilitate cross ventilation and remove excessive thermal gains (Figure 6).

(a) (b)

Figure 6. Views of the new skylights. (**a**) Final view; (**b**) under construction.

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 was 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 entire intervention was developed at low cost and took into account the architectural integration of the final proposal (Figures 7 and 8).

Figure 7. A view of the new ceramic vaults.

Figure 8. The interior view of the aspect of the residential units with vents for aperture.

4. Daylighting Simulations

Two situations have been investigated: overcast conditions (where orientation and hourly and monthly variation) and clear sky with sunny conditions (where orientation and hourly/monthly variations are mandatory). Such variations of hours and orientation have been selected taking into account the necessities of the user with AD and the alterations that they could experience and taking into account the possible discordances in the circadian rhythms.

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 more pleasant than the one registered with artificial luminaires.

Moreover, 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 [22]. 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 because they are symmetrical in the South direction. Within each of these days, several hours have been analyzed. Henceforth, a complete knowledge of the performance of daylighting throughout the year has been achieved. In Figure 9, a summary of sunlight hours in terms of percentage, at four locations, is shown.

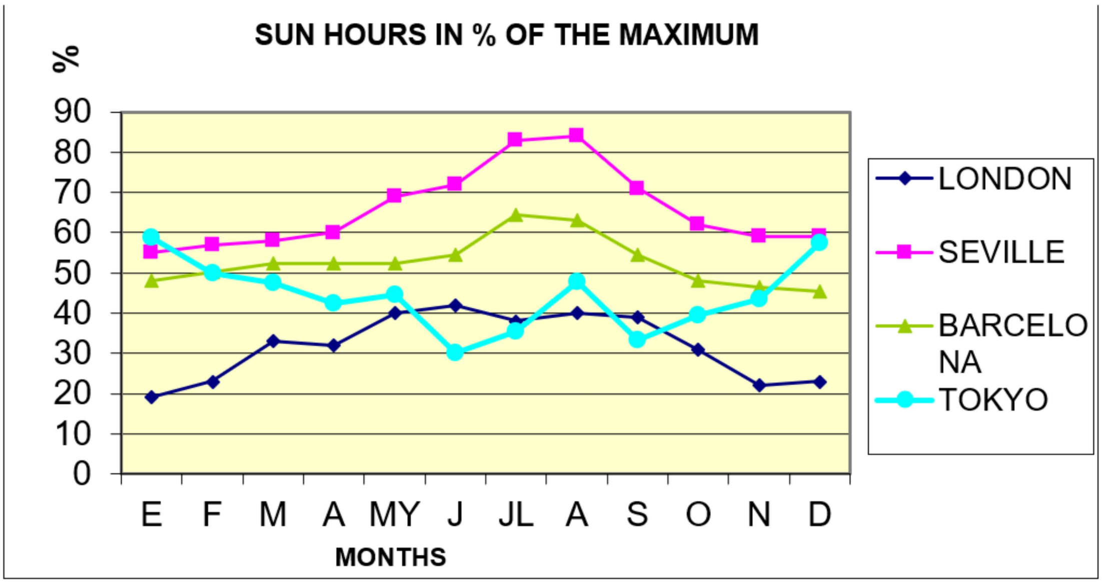


Figure 9. The sunlight distribution by months, in terms of percentage, at four different locations: London, Seville, Barcelona, and Tokyo.

5. Meteorological Data and Coefficients

As explained in the methodology, 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 the general cleaning of the offices was 0.9.

For daylighting calculation, we have used the sky model of Gillet, Pierpoint, and Treado [23], which defines the vertical illumination (in lux) for clear sky based on the azimuth (Φ) and the height (θ) according to the equation below.

$$Ev = 4000 \times \theta 1.3 + 12{,}000 \times \sin 0.3\ \theta \times \cos 1.3\ \theta \times [(2 + \cos\Phi)/(3 - \cos\Phi)] \quad (1)$$

Additionally, in the case of overcast sky, similar to the CIE model, the following equation is used:

$$Ev = 8500 \times \sin\theta \quad (2)$$

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

Table 1. The probabilities of occurrence for overcast and clear sky in Seville (Spain). The State Meteorological Agency, AEMET. Source: the authors.

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 such as partly cloudy, or average, sky.

6. Results of the Simulation

We show below some of the most relevant computer results of the simulations (Figures 10 and 11). Horizontal daylighting values refer to a reference plane located 0.6 m above the floor. The sectional views cut across the loft units through their center point. Notice that the grid points are taken every 1 m in the width, length, and height axes.

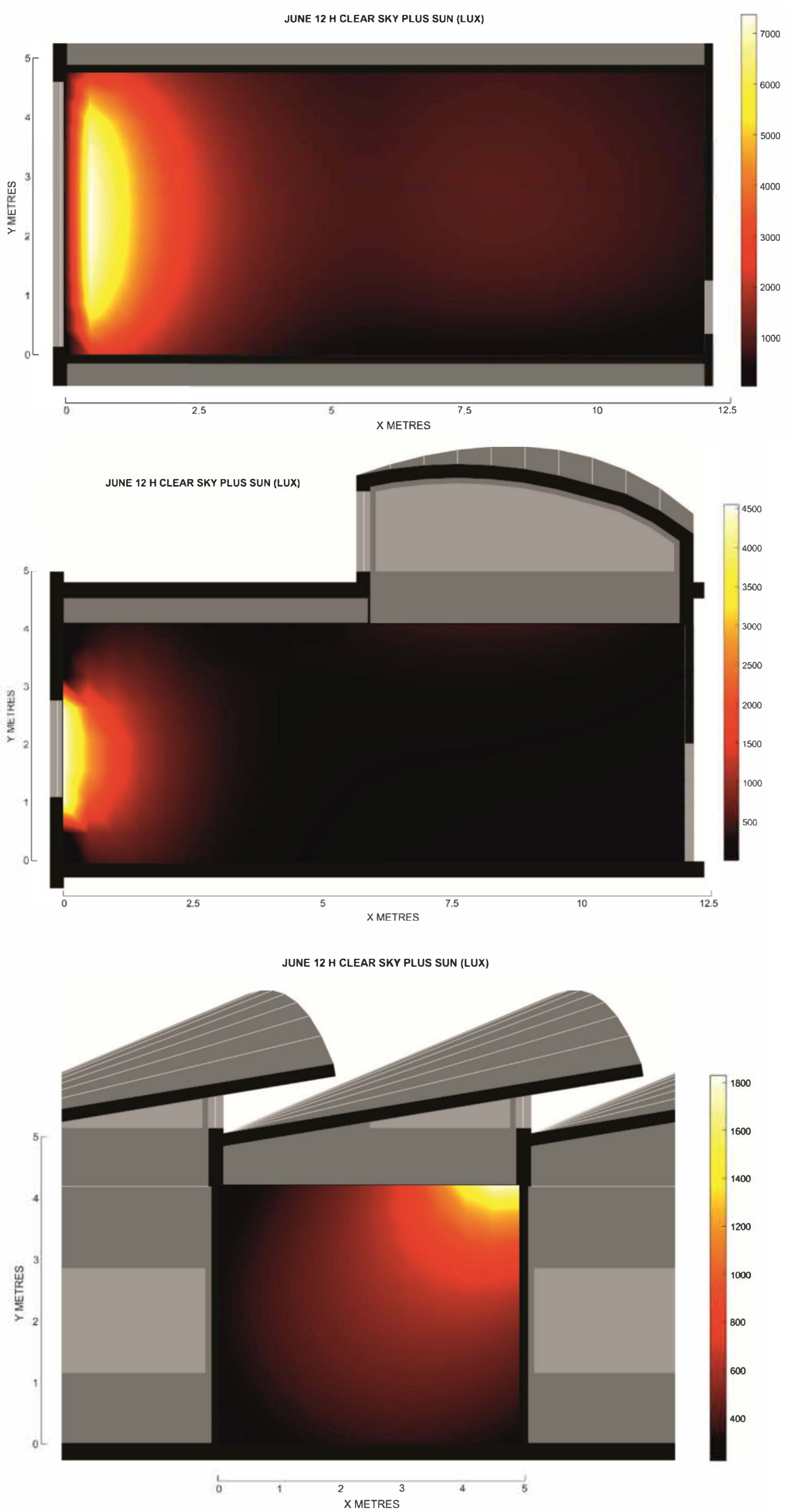


Figure 10. The horizontal and vertical illuminance distribution in an office. June 12:00 h solar time, clear sky plus sun. Values in lux. Source: the authors.

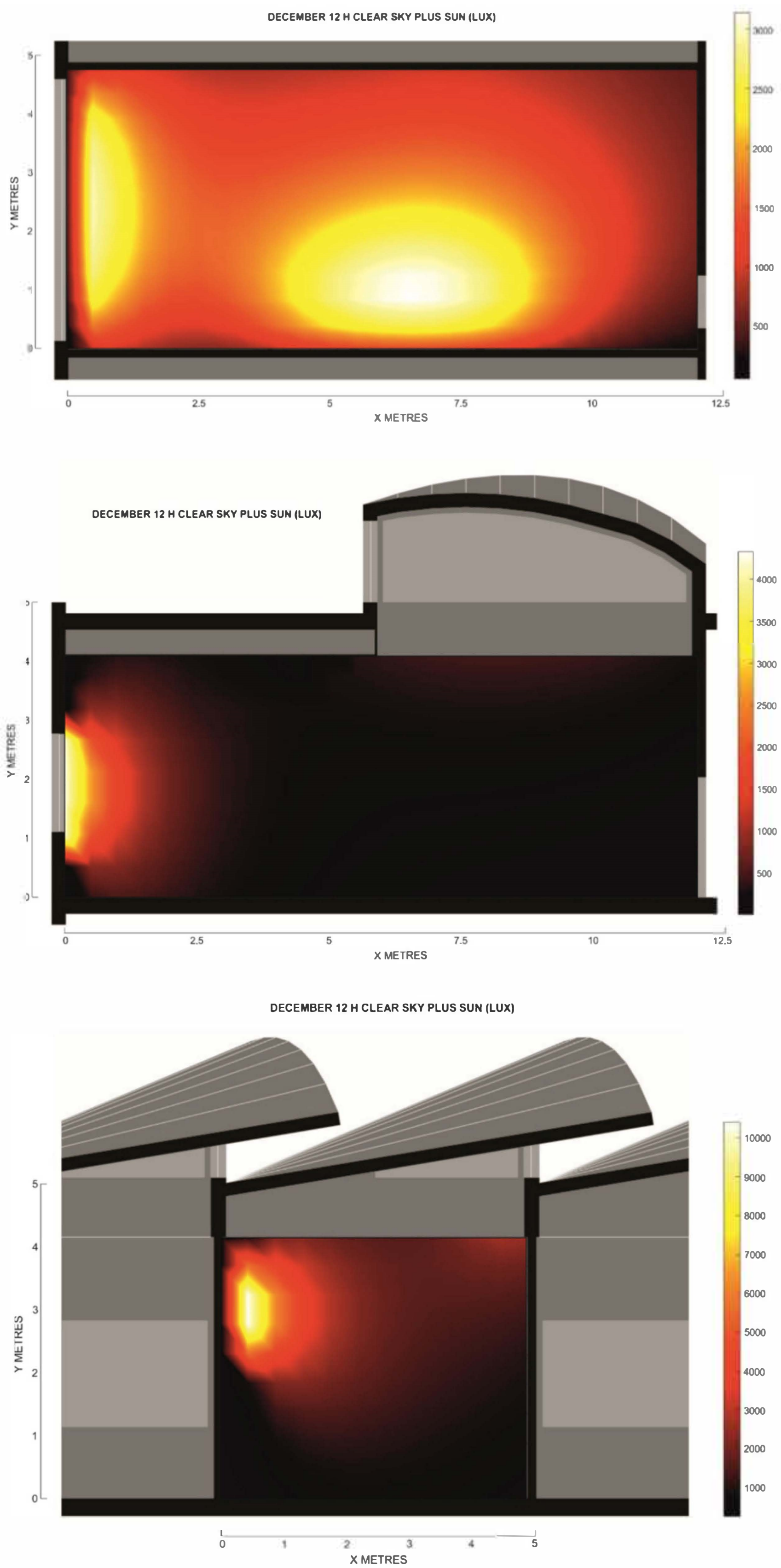


Figure 11. The horizontal and vertical illuminance distribution in an office. December 12:00 h solar time, clear sky plus sun. Values in lux. Source: the authors.

We have to emphasize 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 clear sky with sunny conditions, the daylighting values are higher in the winter solstice than in summer due to the contribution of direct solar radiation to the day-lit interior.

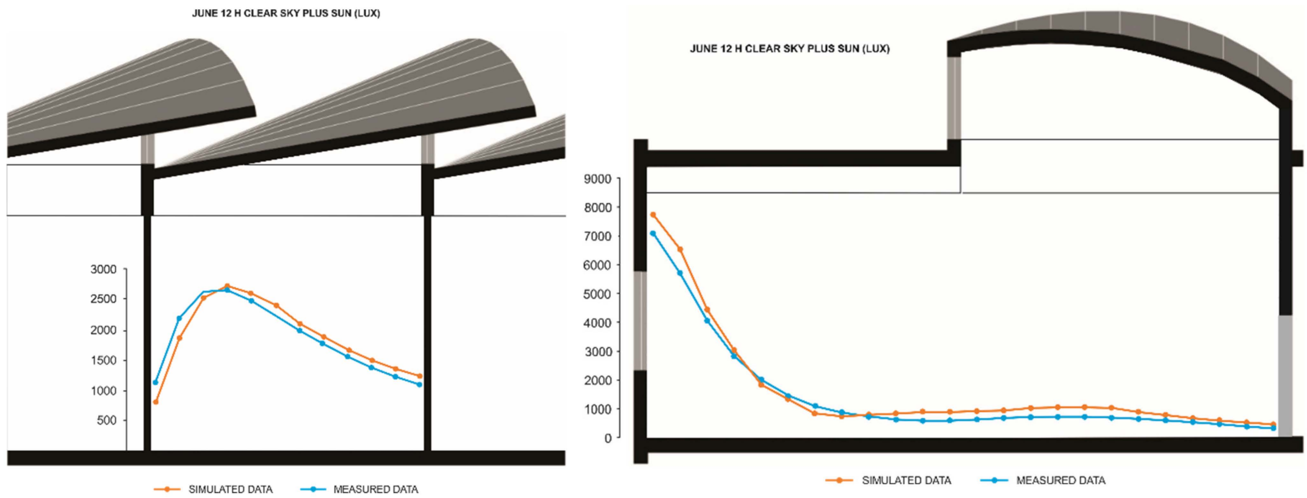
Daylighting in this new system is greatly dependent on solar illumination and is rarely dependent on overcast or clear sky, and this is, in our opinion, an important innovation at least for the sunny climate considered.

7. Monitoring

The authors conducted a thorough monitoring campaign to modulate the range of the simulations and simultaneously check the usefulness of their outputs. An objective validation of our simulation program took place in other controlled experiments [24,25].

We acquired measurements of light with a lux-meter PCE-170A with International Organization for Standardization (ISO) calibration, a measuring range from 0 to 120,000 lux, and an accuracy of ±0.2%. Of these measures, we present a comparison to simulated values for a partly cloudy sky, which corresponded well due to not showing relevant discrepancies.

The slight differences registered between the simulated and measured data were presumably due to the sky being partly cloudy on the days the experiments were performed (Figure 12).



(**a**) (**b**)

Figure 12. The comparison of measured and simulated data for partly cloudy sky at midday on 21 June. (**a**) Transverse axis; (**b**) longitudinal axis. Source: the authors.

8. Conclusions

In general, relatively high and well distributed daylighting levels have been achieved inside the refurbished residential units, which guarantees good conditions at virtually any usable point of the space. The horizontal daylighting ranges over 400 lux, with higher values in winter than in summer. The daylighting levels in the vertical planes are significantly lower and thus are suitable for comfortable living spaces. On the other hand, the new skylights improve the comfort level both in winter and in summer, an improvement that is not obtained at the cost of visual discomfort. The natural light supply systems work effectively, proving to be a project parameter with direct incidence and a meaningful repercussion on the well-being of the person with Alzheimer's disease; they can be extrapolated to any other space of direct use by this population group.

The skylights are currently being monitored. The first data from on-site measurements show that they work properly and a relevant amount of UV rays are ensured.

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 for sunny climates that were underestimated in previous studies.

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