Solar radiation and architectural design in Barcelona

Reconciling protection in summer and gain in winter

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ABSTRACT: The principles of the passive solar house were defined in the 1970s. Since that time, strategies have been conceptualized and tested with different examples built in the USA and in Europe. Models directly related to the Mediterranean climate are rare in this context. They will be the subject of the present study. In these cases, the main issue is to reconcile solar gain in winter and solar shading protection in summer. In addition, summer heat can be lost through natural ventilation. The research will focus on aspects of architectural design to implement alternatives for optimizing control of radiation. The Heliodon 2TM computer software will be used to establish evaluation methods for certifying the energy efficiency of the solutions under study.

Keywords: solar radiation, Mediterranean climate, architecture

1. INTRODUCTION

When addressing the issue of solar radiation in architecture, a separation between strategies for summer and winter are commonly established [1], which, *a priori*, are contradictory (gain and protection). This article, on the other hand, has not chosen this dichotomy. Except in particular cases that are architecturally designed for summer [2] or winter use, designs are usually conceived for good air conditioning throughout the year. Therefore, in this article, we trace different architectural aspects and jointly assess their impact in summer and winter. The objective is to identify compromise solutions that give a good response for both summer and winter.

2. METHODOLOGY

The sun's path follows a daily and seasonal pattern. That path is closely linked to latitude; thus, an architectural form experiences different degrees of exposure to radiation.

In contrast, only approximations may be offered if an attempt is made to quantify the annual radiation received by each architectural surface using theoretical model calculations. The radiation reaching the earth's surface must pass through the atmosphere [3] and cloudiness is a variable that is unpredictable by a model. Therefore, only approximations of absolute values are valid. In contrast, when exposure is equal between surfaces with different orientations or inclinations, their comparative relations will be correct. In this case, the relationships that differentiate one area from another are invariable because they are due to purely positional geometric relations of a flat surface with regard to solar radiation.

These relationships will be explored later on in this paper as they relate to the latitude of Barcelona itself (41:18 N), as a representative of the Mediterranean climate. The computer software tool used is Heliodon 2TM [4], designed by Benoit Beckers & Luc Masset [5]. The program performs calculations in theoretical cloudless conditions [6], without taking into account either the diffuse radiation emitted by the sky [7] or the radiation reflected by nearby surfaces. This method of calculation is not a drawback because its purpose is not to determine precisely the absolute value of radiation received. As indicated above, the aim is to establish comparative relationships between the gain of some surfaces and others. The 2TM Heliodon program is highly useful for this in that it also performs the calculations for the desired time period.

In this study, we systematically assess the radiation accumulated during winter (21-Dec to 21-Mar) and summer (21-Jun to 22-Sep), knowing that in winter, the radiation will be desired, whereas in summer it will not be. The study establishes an assessment procedure that is justified as follows:

Phase 1: design aspects are not incorporated

Compares radiation received by the same surface at different orientations. To do so, a cube form aligned with the cardinal points is used.

Phase 2: design aspects are incorporated

Knowing the different exposures of a surface in terms of its orientation raises design aspects that improve the performance of a project in regard to radiation. Each aspect provides design alternatives with different impact in terms of radiation. In each case, it is possible to determine the alternative that provides the best response to radiation and reconciles the situations of winter and summer. The following table sets out the aspects and alternatives considered:

Table 1: Aspects and design alternatives

ASPECTS	ALTERNATIVES
1- Proportion of the rectangular layout	Analysis of various proportions of the layout

2 – Protection elements of the southern facade	Dimensioning of the horizontal overhangs
3 - Protection elements of the eastern and western facades	Choice of protection: horizontal or vertical
4 – Slope of the roof	Flat or sloped with various inclinations and orientations

3. RESULTS AND DISCUSSION

3.1. Not considering design aspects (phase 1)

The audit consists in assessing the amount of solar energy received by the different planes of a cube the vertical surfaces of which are strictly oriented towards north, south, east and west. It also adds the energy received on a horizontal flat surface corresponding to a hypothetical flat roof.

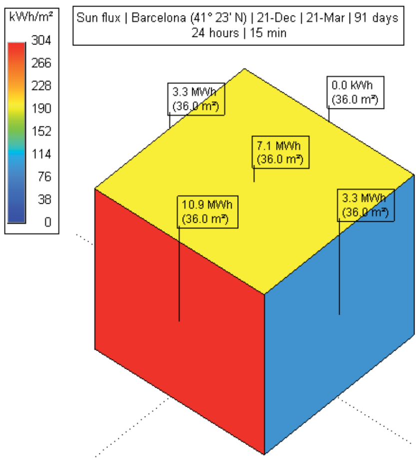

Figure 1: total solar radiation on a 6x6x6m cube, in Barcelona, in winter

Four periods were assessed. The first two correspond to winter (Fig. 1) and summer. The next two were associated with months related to extreme temperatures: the coldest being January, and the hottest, July.

(Fig. 2) summarizes the data obtained in a graph.

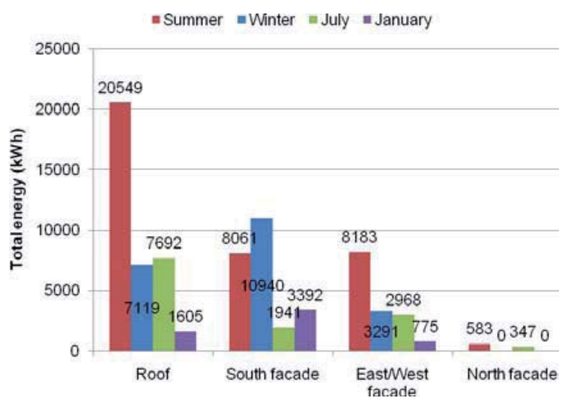

Figure 2: total solar radiation (kWh) on the surfaces of the 6x6x6m cube in Barcelona, in the summer and winter, and in the months of January and July

We should point out the importance of radiation on the roof in summer, which is much higher than the radiation received on any other surface. In July alone, the radiation on the roof is higher than that received in the entire winter.

Regarding the southern facade, it is worth mentioning that the radiation received is approximately 1.4 times higher in winter when compared with summer.

In regard to the eastern and western facades, notice how the radiation received in summer is almost comparable to that received on the southern facade. In contrast, in winter, the radiation received by these facades is only around 30% of that received on the southern facade.

3.2. Considering design aspects (phase 2)

3.2.1. Proportion of the rectangular layout: analysis of various layout proportions

We can say, as a general consideration, that linear forms have better thermal performance throughout the year if they are elongated in an east-west direction, because they are more likely to capture radiation in winter with the large area of exposition represented by the southern facade and, in contrast, they capture very little in summer because the east and west facades are smaller.

The objective is to verify, from the standpoint of solar radiation gain, what the optimal rectangular shape is. The study was conducted based on two parameters: the ratio between width and length and orientation of the shape. Three layout relationships are under study: 3x12m (1:4), 4x9m (1:2 approx.) 6x6 (1:1). The floor area is, therefore, always the same: 36 m^2. Moreover, if the same height (6m) is always used in the evaluation, the interior volume is always the same: 216 m^3. The two rectangular relationships of the layout were evaluated by positioning them based on two orientations: orienting the long facades to the east and west, or orienting the long facades to north and south. A square shape is symmetrical in the two possible orientations and its behaviour is the same. Finally, summer and winter behaviour are assessed seeking a balanced solution that reconciles protection in summer and gain in winter.

(Fig. 3) summarizes the data obtained in a graph.

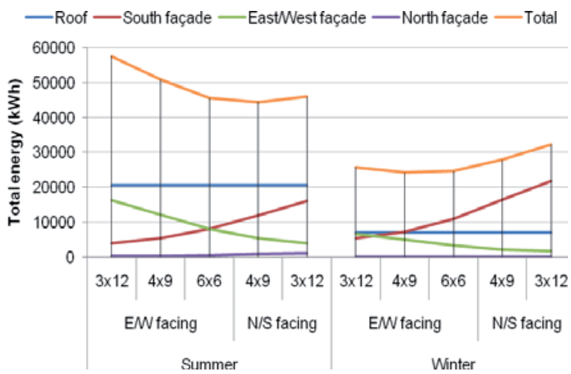

Figure 3: total solar radiation (kWh) on the surfaces of various rectangular shapes, in Barcelona, in the summer and winter

The graphs that show the behaviour of a single surface offer obvious results. Gain increases with the size of the facade.

The interest lies in following the behaviour of the graph that describes what happened in terms of total gain to the volume.

In summer, the 4x9 proportion that orients its long facades to the north and south is the most favourable one since it is the one with lower gain. This proportion (capturing 44,425 kWh) is slightly better than the square option (45,560 kWh) or the long option that is oriented in the same direction (46,018 kWh), and significantly better when compared with the same volume with longer facades oriented to the east and west (between 50,862 and 57,063 kWh).

In winter, the most favourable situation is also to lengthen the volume of the longer facades to the north and south. The capture capacity of the south facade, despite the nearly zero contribution of the north facade, is greater than the sum of the capacity of the east and west facades.

In short, the most favourable relationships, if the purpose is to reconcile winter and summer, are those that have elongated layouts orienting their largest facades to the north and south. The south facade is, undoubtedly, the crucial one due to its previously mentioned high gain capacity in winter.

3.2.2. Protection elements of the southern facade: dimensioning of the horizontal overhangs

If the south side is critical, let us look at how to optimize its performance. The role the south face plays in gain in winter is fundamental. In contrast, in summer, the south facade receives a significant amount of radiation. Therefore, to improve the performance of the south facade it is advisable to lower its gain in summer without being detrimental to gain in winter. In order to achieve this, we must study an alternative design: overhangs for screening the sun.

Given that the sun follows a higher path in the sky in summer than in winter, it is possible to dimension overhangs to screen radiation in summer and allow radiation in winter.

In this section, we evaluate the design of the overhangs seeking the most favourable relationship between the height of the facade to be protected in the summer and the length of the overhangs. An attempt is made to determine the compatible option for the two seasons by performing calculations.

The overhangs are labelled “o” and the height of the façade “h”. We evaluated the following relationships: o=h, o=h/2, o=h/3, o=h/4, o=h/5, o=h/6, without o.

(Fig. 4) shows an illustrative image of the representations by Heliodon, using the case of the longest overhang, o=h.

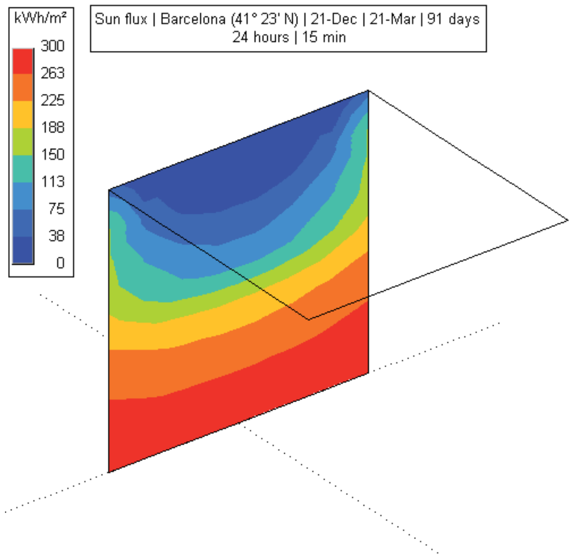

Figure 4: solar radiation with an overhang o=h, in winter

The results are compared using graphs (Fig. 5 and 6) to facilitate understanding and conclusions.

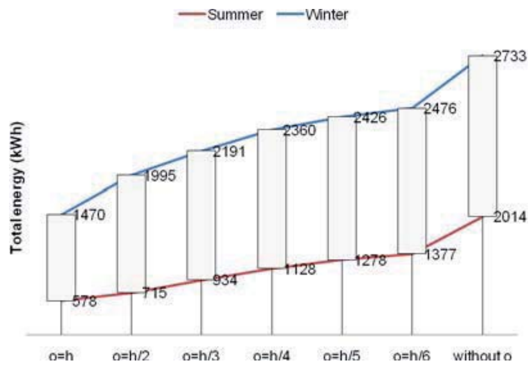

Figure 5: total solar radiation (kWh) with different lengths of overhangs, in Barcelona, in summer and winter

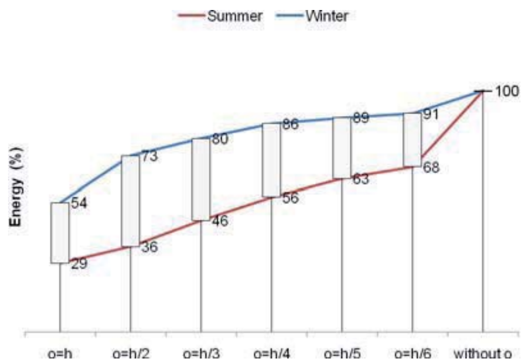

Figure 6: percentage of radiation received with different lengths of overhangs, in Barcelona, in summer and winter

Of all the relationships between the height of the facade and the lengths overhang, the best is o=h/2. In summer, the percentage of intercepted radiation is high and the façade receives only 36% of the radiation. In winter, the same overhang intercepted little radiation and allowed 73% of the radiation to reach the facade.

3.2.3. *Protection elements of the eastern and western facades*: **choice** *of horizontal or vertical protection*

The particularity of the east and west facades is that each, in summer, receive as much radiation as the south facade. This does not occur in winter. The amount of radiation received by the two facades does not equal the radiation received by the south facade. Therefore, if we want to improve performance in comparison to radiation on these facades, we must strengthen protection in the summer, while trying not to harm the lower winter gain. What type of protection would be proposed for this purpose?

The east and west are associated at the time of sunrise and sunset. Radiation is quite flush at that time of day. This implies, geometrically, an angle of incidence of radiation that is quite perpendicular to the vertical planes and, in theory, increased gain. But in these instances, radiation must pass through thicker atmospheric layers, so its effect is reduced. In layman's terms, we say the sun doesn't heat as much.

Furthermore, in winter, sunrise and sunset occur in the southeast and southwest respectively. In contrast, in summer, they occur in the northeast and northwest. Therefore, in summer, the radiation around the east and west occupies many more hours a day and, much of the time, the height of the sun is considerable and radiation is no longer flush.

Given the above, the question of how to approach effective solar protection on the east and west is reformulated as follows: Should the overhangs be horizontal (as in the case of southern orientation) that impede radiation from above, or should protections be vertical to intercept flush radiation?

To respond to this dilemma, the Heliodon software program was once again used, assessing the radiation received by an eastern oriented 3x3 vertical surface at Barcelona's latitude.

The response was evaluated in summer and in winter, with no protection, with a horizontal overhang (Fig. 7), with vertical protection on the north, and with vertical protection on the south (Fig. 8).

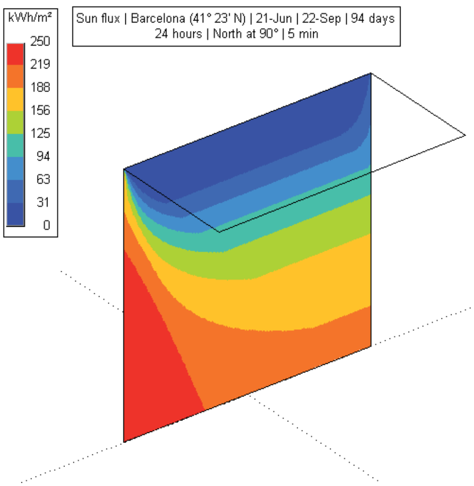

Figure 7: solar radiation received by an eastward oriented surface, in summer, with overhang

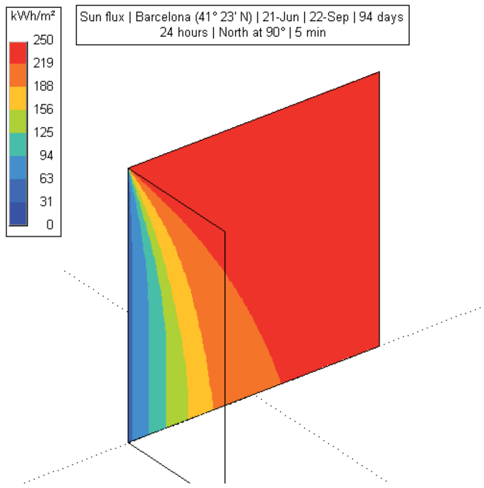

Figure 8: solar radiation received by an eastward oriented surface, in summer, with vertical protection on the south

All protective elements will be exactly the same size to compare the effect of only changing their position. Thus, we can prepare a chart comparing the absolute values (Fig. 9) and another graph comparing the percentage received in comparison to the situation without protection (Fig. 10).

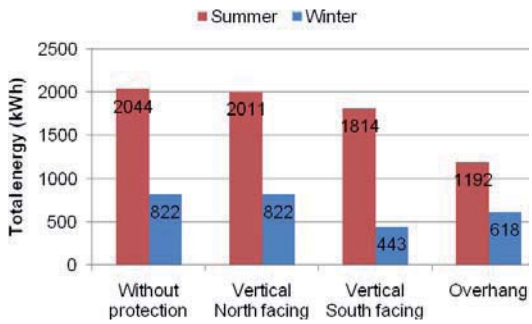

Figure 9: total radiation (kWh) received by an eastward facing surface with various protective elements, in Barcelona, in the summer and winter

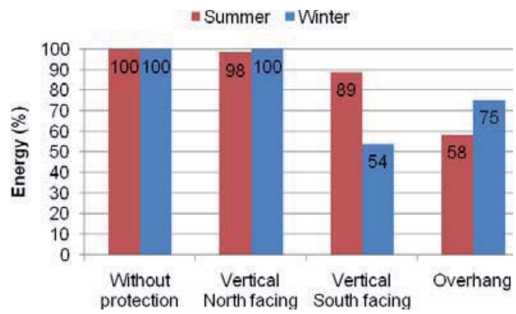

Figure 10: percentage of radiation received by an eastward facing surface with various protective elements, in Barcelona, in the summer and winter

The vertical protective effect on the north is negligible. The discussion comes down to choosing between vertical protection on the south or the overhang. The overhang is the more successful of the two. It reduces the amount of radiation received in summer (58%) and allows a greater amount of radiation to be received in winter (75%).

Another case study, linked to the same east and west orientations, is that of radiation control shading slats to protect a window. Again, the discussion is in relation to the optimum position. Considering the previous study, it is advisable to suspect that horizontal positioning of the slats will be most suitable.

To resolve the discussion, a proposal was made to analyze the behaviour of a 3x3 meter, westward facing opening, on which the same shading slats are placed, changing only their position: horizontally (Fig. 11) or vertically (Fig. 12). The arrangement of the slats is every 30cm and they protrude 30cm above the surface of the opening. The radiation calculations are performed for two study periods: summer and winter.

The case in which no shading protection is used is also added to the assessment. This makes it possible to comment in terms of percentage of radiation received in relation to a hypothetical case with no shade protection.

To facilitate comparison, two bar graphs are used to show the results. The first shows the absolute values of radiation received (Fig. 13) and the second the percentage values of radiation received in comparison with the case of no shade protection (Fig. 14).

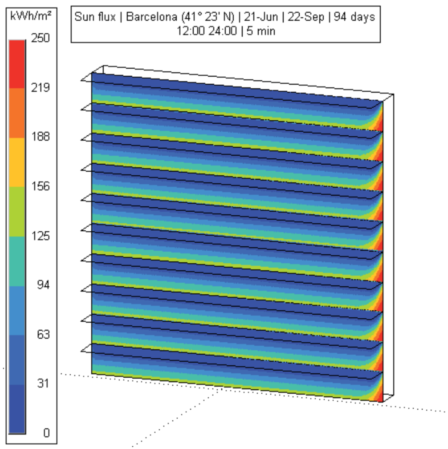

Figure 11: solar radiation received by an opening oriented towards the west protected with horizontal slats, in summer

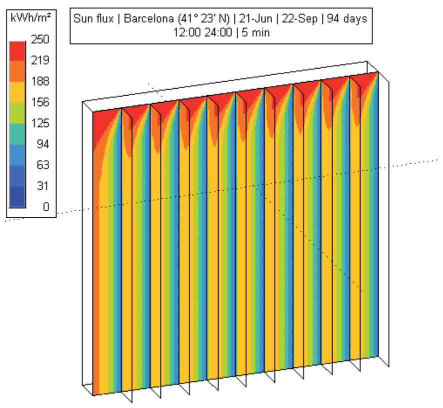

Figure 12: solar radiation received by an opening oriented towards the west protected with vertical slats, in summer

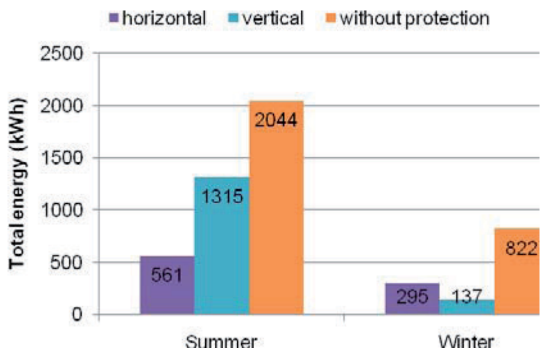

Figure 13: total radiation (kWh) received by a westward facing surface with protective slats, in Barcelona, in the summer and winter

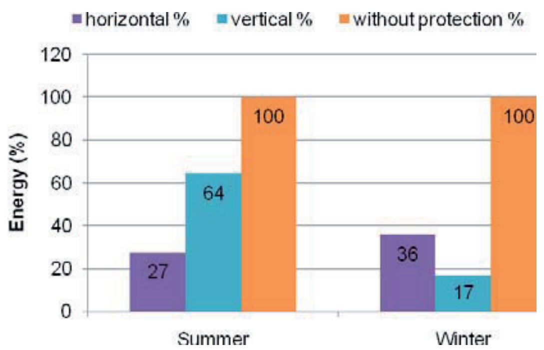

Figure 14: graph comparing the percentage of radiation received by a westward facing surface with protective slats, in Barcelona, in the summer and winter

The benefit of horizontal shading is clearly superior to the vertical shade protection. In winter, when radiation is desired, 36% versus 17% of that possible is received. It is in summer, however, when the benefit is blatantly superior. When the radiation is not desired, the total received is lower: 27% versus 64% of that possible.

3.2.4. Slope of the roof: flat or sloped with different inclinations and orientations

In summer, the radiation received by a horizontal roof is twice that received by a southern facade of the same surface. In winter, since the sun's path is lower in the sky, the same roof receives 75% of the radiation hitting the southern facade. This reflection demonstrates the great importance of the roof in bioclimatic design.

In this section, the proposed exercise is simple. The same floor area is covered with roofs with different inclinations and orientations; the radiation received in each case is recorded.

An illustrative image of the simulations of the radiation received is shown below. It corresponds to the radiation received in summer by a roof with an inclination of 50% to the south (Fig. 15).

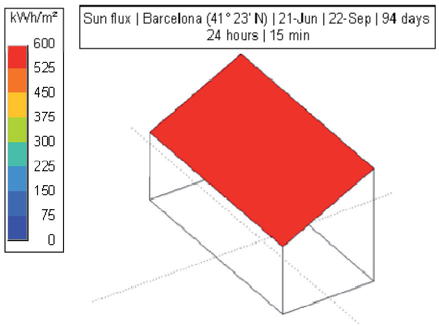

Figure 15: solar radiation received in summer by a roof with a 50% inclination towards the south

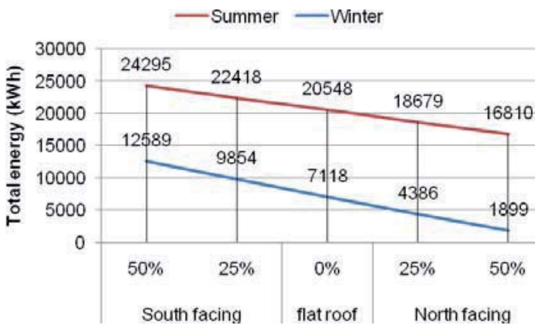

Figure 16: total radiation (kWh) received by the same roofs with different inclinations and orientations, in Barcelona, in the summer and in winter

The reading of the results (Fig. 16) found that, as the roof leans farther towards the north, the variations between the gains in summer and winter became more pronounced. A southward facing roof with a 50% inclination has double the gain in summer than in winter, and with the same inclination, but oriented northward, the exposure is almost 10 times higher in summer.

In line with the above discussion, a flat roof is a convenient option at Barcelona's latitude. The radiation received in summer is situated exactly at the point of balance between the roofs with the same slope but facing south or north. In contrast, in winter, there is reduced gain compared with roofs facing south; but, it will never be as dramatic when compared with north-facing roofs.

It is worth recalling that, in any event, the radiation received by the roof does not move inside in the form of hot air that descends to ground level. Lighter, warmer air only rises. The deleterious effect is the radiation exchange with the user. The roof area, heated if it receives strong sunlight, emits radiation toward the user jeopardizing comfort.

4. CONCLUSION

The modelling of architecture linked to controlling radiation is entirely feasible. Geometric relationships exist between the sun's position, exposure of the form to radiation and the design of protective shading devices. The sun's path is characteristic at each latitude. Therefore, from the standpoint of radiation, it is possible to associate form with a certain latitude. For example, horizontal fixed protective shading elements will be most effective in all directions at Barcelona's latitude (Fig. 17). Due to the existence of geometrical laws that describe the regularity of the sun's path, Heliodon 2TM software is an effective tool that enables quick calculations for long time periods. We can deduce, from our findings, relationships that compare the radiation received by different design solutions and, therefore, their efficiency.

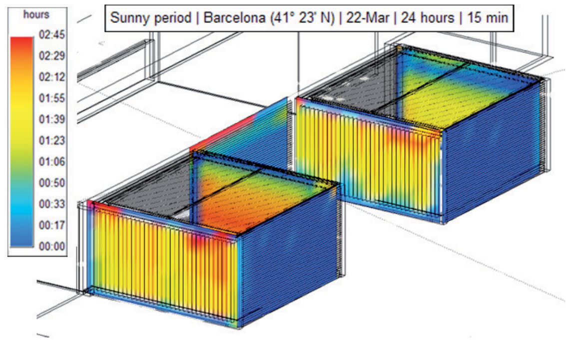

Figure 17: real case: bar of the School of Architecture of Barcelona: vertical (left) and horizontal (right) slats.

5. ACKNOWLEDGEMENTS

As we could not have it any other way, we would like to express our gratitude to Benoit Beckers, professor at the University of Technology of Compiègne (UTC, France) for having placed Heliodon 2TM at our disposal. It is useful software for the architectural design process when the aim is to prepare a model based on energy efficiency. Heliodon 2TM offers synthetic responses with rapid calculations and expressive representations.

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