

## **DYNAMIC DAYLIGHT SIMULATION AND VISUAL COMFORT SURVEY IN MEDITERRANEAN CLIMATE. CASE STUDY IN OFFICE BUILDING.**

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### ABSTRACT

This work shows a particular study in a single office in Barcelona, with an exterior Sud-East façade. Daylight simulations are made with DAYSIM (2010), dynamic validated software based on RADIANCE (1990-2002). Also, these results are compared to: visual comfort surveys and luminance and illuminance data obtained from field measurements (in situ). The field measurements were made during 20 days of March of 2012, with illuminance sensors, luminance camera, and meteorological station. The comparison of the results between simulations and field studies has shown the importance of a correctly calibrated model to get reliable data, thus improving energy performance and visual comfort of users.

### KEYWORDS

Daylight, Daysim, Visual Comfort, Luminance, Illuminances, Glare, Mediterranean Climate.

### INTRODUCTION

To reduce energy demand, in recently constructed buildings, to achieve a “nearly zero or zero energy building” label, it is necessary to implement intelligent control systems and energy efficient technologies based on sensors and actuators (Dubois & Blomsterberg, 2011). In this way, to establish an optimal solution, field studies and simulation scenarios are required to know the potential of energy savings along the year. In office buildings, an important part of energy demand is electrical energy for artificial lighting and air conditioning systems (HVAC). Moreover, it is very important when assessing the performance of daylight, to account and consider the amount of daylight that causes discomfort problems to users (Nabil and Mardaljevic, 2005)

There is a complex relationship between many factors that affect the amount of daylight for potential savings and the amount of glare produced by daylight sources (Torres and Sakamoto, 2007).

In a Mediterranean region, such as Barcelona, with a temperate, sunny climate, there is a considerable availability of daylighting during the day and year around. This availability of daylight can contribute to maintain the minimum illuminance level required for office tasks. The main possible disadvantage of the use of daylight is that it is variable during the day and year. For this reason, a dynamic analysis of daylight availability is required, taking into account the different sky conditions and the orientation of the façade.

To acquire a good energy efficient performance in buildings, it is necessary to assure the environmental comfort for users, without the comfort of users the solutions are not useful (Fontoynt, 1999).

The first part of the reference project has the objective to characterize the current situation of the building in terms of Indoor Environmental Quality (IEQ), energy consumption and building operation, and energy harvesting characterization.

The focus of this paper is on the field data obtained, dynamic simulations, and luminous environment surveys of daylight and lighting performance.

### CASE STUDY

This work shows the office building's studies in “*La Ciutat de la Justicia*”, head office of courts of the city of Barcelona and l'Hospitalet de Llobregat. The studied offices are located in the building named “D” on the 11th floor. This work presented the results and simulations that were made in a single office, shown in Figs.1-2, in artificial lighting and daylighting conditions, taking in count the work place of user detailed in Fig.2.

### WORK METHOD

Simulations were made with the current model or scenario (baseline) and then were compared the control systems introduced (finish point), in order to evaluate the energy savings in lighting and comfort parameters obtained related to the luminous environment.



Figure 1. Single office picture.

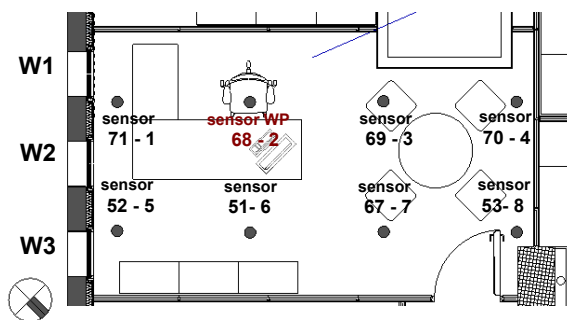


Figure 2. Single office plan with horizontal illuminance sensors (real and simulated).

### Post Occupancy Evaluation (POE)

In this project, Post Occupancy Evaluation (POE) was made by field measurements (spot measurements array shown in Fig.2) and IEQ Surveys, to obtain a wide range of information about the building performance. Experimental data were collected to obtain accurate data of the daylight availability, users profile, users' behaviour, etc.

This work shows particularly Lighting and Daylighting monitoring data related to a Daylight and Lighting environmental survey.

### Visual environment and Visual Comfort survey.

The survey campaign was carried out from March 28th until April 20<sup>th</sup> of 2012, during the campaign measurements period. The survey was divided in two parts: a) comfort survey (twice a day) and b) environmental survey (only once by all building users). The results of the comfort survey could be compared with the measurement data, in order to obtain relations between the simulated comfort probabilities and the user perception. On the other hand, the environmental survey has the objective to evaluate satisfaction of the occupants with the environment over the year.

#### a) Questions in comfort survey:

-How do you perceive the level of lighting in the room?

-How would you like it to be the level of lighting in the room?

-Which of the following statements reflects your situation?

### Global solar radiation available.

A meteorological station was installed on the roof of the building, just over the single office. Global radiation data was collected (5 min time step) by a pyranometer, from 28/02 to 19/04 of 2012. Solar beam and solar diffuse were extracted by TRNSYS(a) from real global radiation data from solar radiation processor, based on the relationship developed by Reindl, TRNSYS(b).

### Occupation user's profile.

The type of user (active or passive), the power installed (lighting) and hours of use directly affects the power consumption in artificial lighting.

In order to establish an occupation profile to perform the simulations (type and hours of use, according to the turn on/off from user) and electric consumption, data was obtained from the power meter installed in the artificial lighting system in the single office from 28/02 to 19/04 of 2012.

The use of the single office was established in 11 hours on weekdays, with intermediate breaks and lunch time, running from: 8.00 to 19.00 hours. Lunch from 13.16 to 14.16 hs. and a half-hour breaks in the morning and evening.

### Spot measurements: Lighting and Daylighting.

The indoor measurements were taken in situ, as detailed below in Table 1-2, in order to obtain information to calibrate simulation model. In other words, the simulation model is accurate to the point of reflecting the current operating conditions.

-Horizontal illuminance: the array of eight indoor prototype sensors were located according the work place and windows location and geometry of the office for horizontal illuminance data, in order to calibrate the resulting from Illuminance file (\*.ILL) from DAYSIM simulations, according to the following Table 1:

Table 1.

Real and simulated sensors coordinates of horizontal illuminance.

Real Sensors	DAYSIM sensors	Model coordinates (45° Model rotation)		
		x	y	z
71	1	0.15	0.60	0.85
68*	2	-1.18	1.95	0.85
69	3	-2.53	3.29	0.85
70	4	-3.86	4.62	0.85
52	5	0.91	1.37	0.85
51	6	-0.42	2.71	0.85
67	7	-1.76	4.05	0.85
53	8	-3.09	5.38	0.85

\*consider work place (WP).

**Luminance camera.**

Photographs with luminance camera were taken on two different hours and sky, as detailed in Table 2, to obtain luminance values and distribution in the visual field of the user.

Table 2.

Luminance camera measurements: sky conditions and date and time.

DATE	TIME	SKY CONDITIONS
21/03/2012	12.00 h	overcast
23/03/2012	09.50 h	clear

CALIBRATION AND MODEL.

**Dynamic daylight simulation DAYSIM.**

In this paper the focus is to determine the contribution of daylight in the studied office to adapt the artificial lighting level required, considering different lighting control strategies using manual and autonomous occupancy sensors, lighting sensors and illuminance control to lighting systems. Also, annual dynamic simulation is made to complement the monitoring data in daylight conditions.

The process to build the model is: define geometry and materials characteristics of the single office; calibration process with the available real data in the monitoring period (equinox); annual simulations; and finally, adjust the model based on comparison.

The model was made with the available data from monitoring and spot measurement by prototypes autonomous sensors, and then a comparison of real data and simulated data was made.

a) Geometric definition.

The model was made by SKETCHUP, a 3-dimensional model exported to 3Ds format (\*.3ds file), according to the reference planes provided. Total surface of the single office is 22.84 m<sup>2</sup> with a Southeast facing façade with 3 windows of 5,72 m<sup>2</sup> total glazing surface.

b) Assigning materials.

Materials were assigned in the SKETCHUP, from the combined library from DAYSIM, as shown in Table 3.

c) Climate file.

For weather conditions the climate file: ESP\_Barcelona.081810.IWEC was loaded and then a weather file (\*.Wea) every 5 min was created by DAYSIM. The resulting file was adjusted from 28/02 to 19/04 with the values of direct and diffuse horizontal radiation, according to data obtained from meteorological station.

Table 3.

Materials assigning to 3D model in SKETCHUP from DAYSIM material library.

CONSTRUCTIVE ELEMENT	MATERIAL NAME	MATERIAL PROPERTIES			
		MATERIAL TYPE	REFLECTION COEFFICIENT (R, G, B)	SPECULARITY	ROUGHNESS
Pavement	GenInt-Floor	O*	0.2	0	0
Ceiling	GenInt-Ceiling	O*	0.8	0	0
Interior walls	GenInt-Wall	O*	0.6	0	0
Windows	Generic-Double-Glazing 72	T*	0.35	0	0
Exterior facade	Outside-Facade	O*	0.78	-	-
Exterior Pavement	Outside-Ground	O*	0.2	0	0

O\* =opaque element, considered pure reflector diffuser.

T\* =translucent element: selective glass (double), visual transmittance 72% visual and 78% transmissivity.

d) Viewpoint for simplified calculations of DGP (Daylight Glare Probability).

The position of the observer was defined at the workstation place or work place (point 68) with two different directions to the simplified calculations of daylight glare probability or DGP% (\*.vf), according to the following Table 4:

Table 4.

Details of viewpoint file (\*. Vf).

REAL SENSOR	DAYSIM SENSORS	TYPE OF SENSOR	-VP (X,Y,Z)	-VD (X,Y,Z)	-VH -VV
68	1	Vertical Illuminance Workplace	(0.36,1.9, 1.2)	(+1,0,0) Direction to opposite wall	180°
68	2	Vertical Illuminance Workplace	(0.36,1.9, 1.2)	(0,-1,0) Direction to window	180°

VP= view point; VD= view direction vector; VH= view horizontal size; VV= view vertical size.

e) Lighting and daylight control systems.

There are 4 luminaires with 2 x T5 HE fluorescent tubes (28 watts) with electronic ballast, total power installed is 9,8 W/m<sup>2</sup>.

For the prediction of the annual energy consumption for artificial a manual and automated control of lights and blinds using the algorithm implemented in Lightswitch-2002 DAYSIM (Reinhart, 2004) was simulated. This algorithm analyzes the behaviour of office lighting in terms of energy efficiency under different lighting control schemes.

Various schemes were made to obtain annual energy performance with different lighting control system and strategies (15 combinations).

For DAYSIM the following modes of operation as shown in Table 5 were used.

Table 5. Simulation of lighting operating modes.

OPERATION	ENTRY VARIABLES	THRESHOLDS
Power saving mode	occupancy, illuminance, activation timer, energy consumption	Occupation: on / off Delay time: 2 min Power Consumption (W)
Visual comfort mode	Dimmer actuator fitting, daylight visual comfort index: DGP %,	<0.4 no visual comfort glare > 0.4 visual discomfort

**COMPARISON RESULTS**

**Horizontal illuminance values.**

*Availability and acquisition of field data.*

The illuminance sensors that were used are prototypes and also they are part of the project development. The sensors are designed to consume very low energy and are communicated with the computer by wireless. During the campaign there were some connection problems and in consequence, some data was missed. The illuminance measurements were made as part of a larger campaign, and it was not possible to repeat the measurements, in order to not delay the rest of the campaign.

It is expected to soon complete the analysis of results of new measurements in situ and subsequent comparison with simulation in DAYSIM, as well as new campaigns are planned also for the summer season 2013.

*Field data from 22/03/2012 and dynamic simulations.*

There are consistent correlations of the horizontal illuminance levels compared measured data and simulation results. In the Figs. 3-6 are shown comparisons between real and simulated results by

DAYSIM. However, a recording problem in sensor 71, very close to window 1, has led to a “lack of information from 11.00 to 15.00 h. in this significant point, taking in account the proximity with the work place (sensor 68).

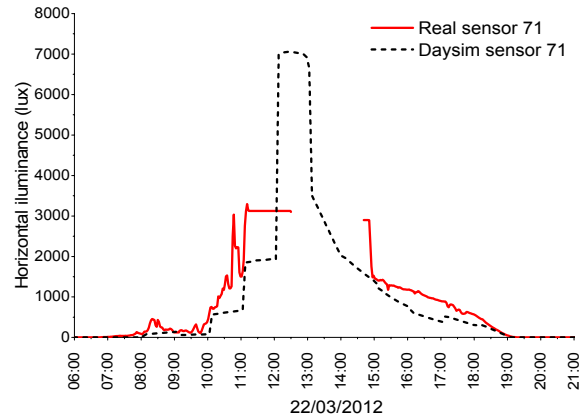


Figure 3. Graphic of illuminance (horizontal) values from sensor 71 – window 1, (real and simulated).

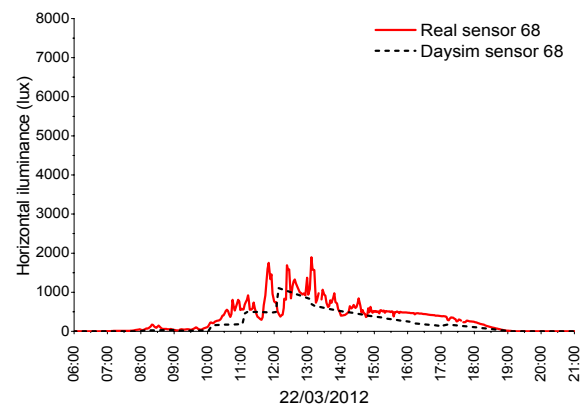


Figure 4. Graphic of illuminance (horizontal) values from sensor 68 work place (real and simulated).

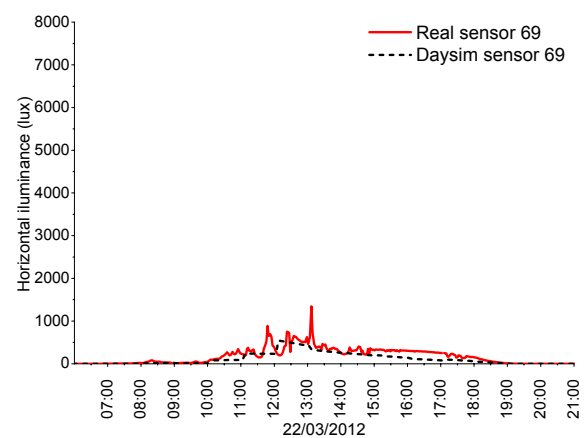


Figure 5. Graphic of illuminance (horizontal) values from sensor 69 (real and simulated).

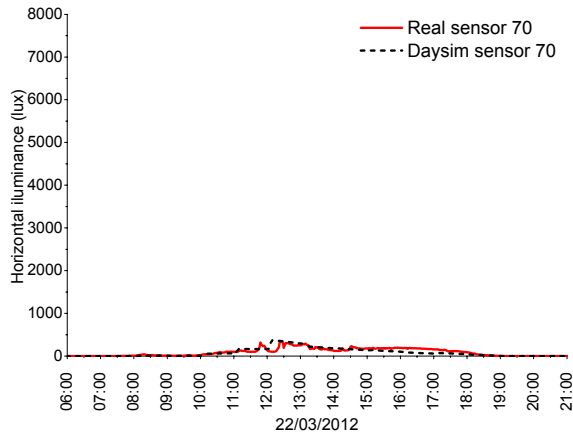


Figure 6. Graphic of illuminance (horizontal) values from sensor 70 (real and simulated).

**Luminance values (luminance camera) from 21 and 23 of March 2012 (equinox period).**

To calculate daylight glare, a simplified method for DGP (daylight glare probability) is used, (Wienold, 2009), by DAYSIM dynamic simulation. The annual calculations of DGP % are correlated with measured data with the luminance camera, although there are different magnitudes (probability of glare and luminance values, source of glare, etc.)

In daylight conditions during intermediate season (spring and autumn) the critical hours considering direct and indirect glare conditions are from 9,00 am to 11,00 am in clear sky conditions (up to 372.000 cd/m<sup>2</sup>), as shown in Fig 7. With overcast sky conditions the probability of glare is considerable reduced, as shown in Figs. 8-11, in luminance camera photograph and false colour analysis (maximum of 480 cd/m<sup>2</sup>).

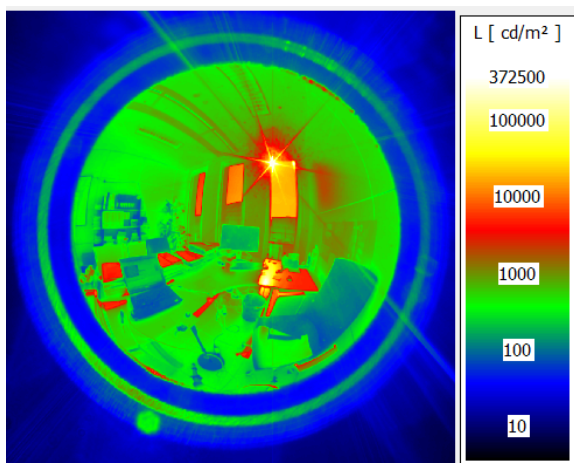


Figure 7. False colour analysis (maximum 372500 cd/m) from luminance camera photograph from 23/03 at 9:50 (clear sky) in daylight conditions



Figure 8. Luminance camera photograph from 21/03 at 12.03 (overcast sky) from work place in daylight conditions.

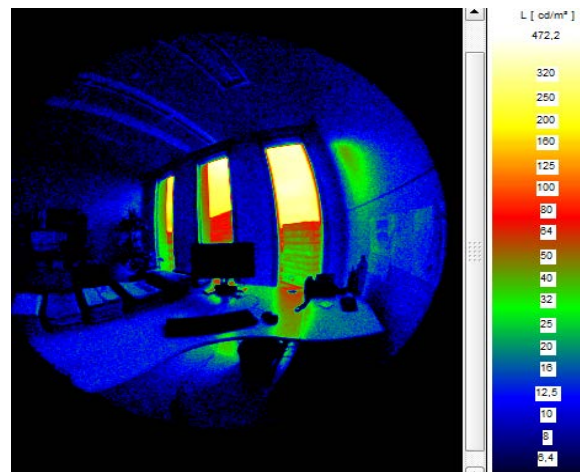


Figure 9. False colour analysis (maximum 472,20 cd/m<sup>2</sup>) from luminance camera photograph from 21/03 at 12.03.



Figure 10. Luminance camera photograph from 21/03 at 12.03 (overcast sky) from work place in artificial and daylighting conditions.

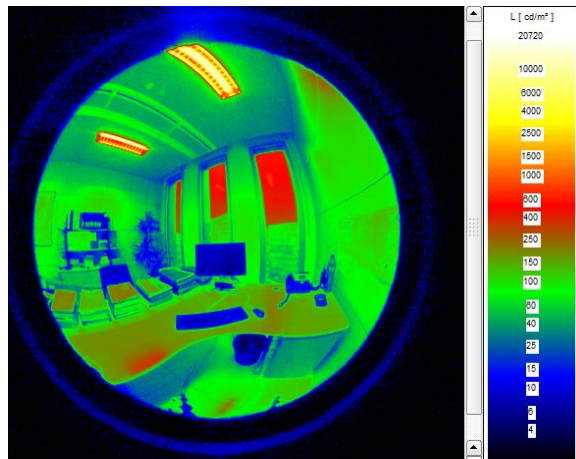


Figure 11. False colour analysis (maximum 20.720 cd/m<sup>2</sup>) from luminance camera photograph from 21/03 at 12.03.

### Dynamic and static simulations and visual comfort surveys.

Visual comfort surveys are made in two single offices (symmetric).

Visual comfort surveys show that both users have access to the blinds, and 46% of responses indicate that they have operated curtains to regulate natural light, as shown in Fig.12.

The remaining 54% show that could be due to two situations: 1) natural light is adequate and they do not need to operate the blinds, or 2) the user does not operate the blinds, regardless the level of natural light available. Therefore, taking into account that 46% of the responses indicate that the user was operated the blinds, but the remaining 54% can be part of a regular act on the curtains (22% operate blinds to have more daylighting, and 24% to avoid dazzling).

Also, analyzing individual responses of the three different offices (two single and one open plan offices) can conclude that users of the work areas near the windows or individual areas are semi-active or active control in reference to daylight availability.

*Detailed results of question about operation of shading devices (blinds) Fig.12.*

Which of the following statements reflects your situation?

-15%: I have the blinds down because there were already down.

-24%: I lowered the blinds to avoid dazzling.

-39%: I have the blinds up because there were already up.

-22%: I opened the blinds to have more daylight.

-0%: I have no access to operate the blinds and I am dazzled.

-0%: I have no access to operate the blinds but I am not dazzled.

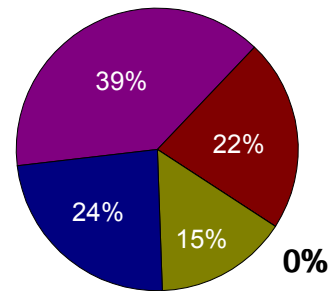


Figure 12. Graphic of the comfort survey results of two single offices (symmetric): blinds operation in daylight condition.

*Resume of questions about daylighting preferences:*

-How do you perceive the level of lighting in the room?

-How would you like it to be the level of lighting in the room?

51 user's responses out of a total of 59 (86%) consider that the level of daylighting of the room is adequate. The same percentage of users would not change the level of lighting.

### CONTROL STRATEGIES RESULTS

The simulation results by DAYSIM show different daylighting indexes (DF%, DA%, UDI%, etc) and annual energy consumption of each of the models simulated. This data feeds an autonomous control system algorithm to operate the artificial lighting system.

#### Static vs. dynamic control shading devices.

**Calibrated Model 1** (On/Off manual control of lighting systems).

The results of dynamic simulations show that the minimum of annual electricity demands (285.1 kWh) is obtained with static solar protection device (include in the geometry of buildings, without blinds operation) The DA (35%) and UDI<sub>100-2000</sub> (78%) index in work station are the highest of the all of simulations of calibrated model, but this occurs because the model only taking into account the horizontal illuminance in work station to operate the on/off artificial light system, although conditions are not comfortable for the users.

**Calibrated Model 2** (On/Off manual control of lighting systems).

The results of annual electricity demands with dynamic shading device (interior blinds) to avoid DGP > 0.40 is 441.2 kWh, with DA=12% and UDI<sub>100-2000</sub>= 33%, decreasing UDI<sub>>2000</sub> to 1%.

**Calibrated Model 3** (On/Off manual control of lighting systems).

The results of annual electricity demands with dynamic shading device (interior blinds) to avoid

sunlight > 50W/m<sup>2</sup> is 383,5 kWh, with DA=12% and UDI<sub>100-2000</sub>=1%, increasing UDI<sub>>2000</sub> to 33%.

These results shown that the discomfort probability is not caused only by sunlight in the workplace, but also by high levels of vertical illuminance. For that is necessary to consider solar and daylight control devices to obtain visual comfort of users.

**Predicting automated control to switch on/ off and to operate shading devices.**

The results with automated blinds show that the optimal solution in energy savings (152.1 kWh) is the combination of automated switch off and photo-sensor to dimming the artificial lighting system and automated blinds, whose results appear in Fig.15.

This solution assures the optimal relation in energy saving and visual comfort of users.

*-Lighting control configurations from Figs.12-15:*

- 1: on/off: manual/ occupancy sensor
- 2: on/off: occupancy sensor/ occupancy sensor
- 3: on/off + dimming: manual/manual + photocell.
- 4: on/off + dimming: manual/sensor + photocell.
- 5: on/off + dimming: sensor/sensor + photocell.

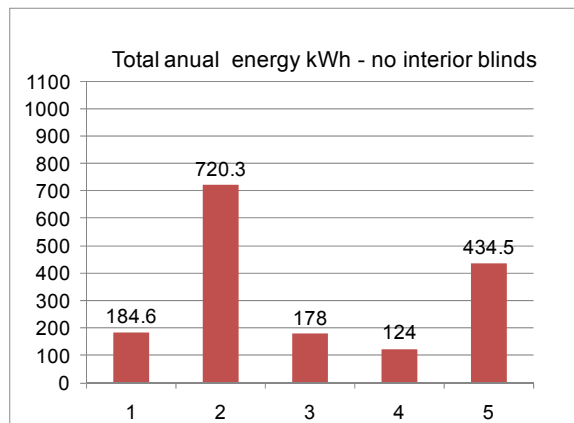


Figure 12. Total annual energy consumption in kWh, with no interior blinds.

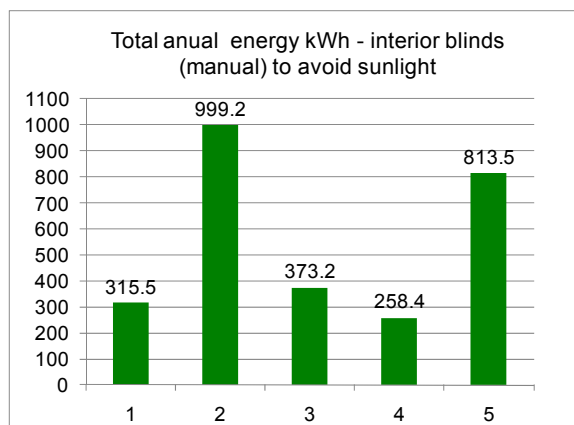


Figure 13. Total annual energy consumption in kWh with blinds operated manually (to avoid Sunlight).

With active users operating the blinds manually, the result of annual electricity is 258,40 kWh to avoid sunlight and 283,10 kWh to avoid DGP > 0.40, shown in Figs. 13-14.

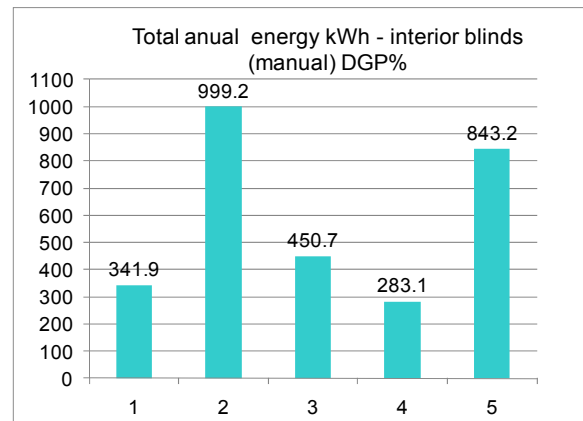


Figure 14. Total annual energy consumption in kWh, with no interior blinds, with blinds operated manually (to avoid DGP% > 0.40).

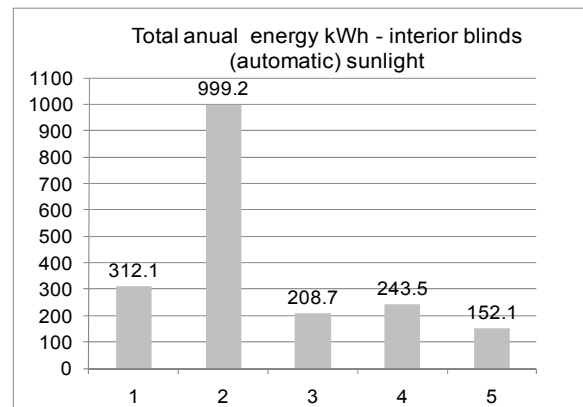


Figure 15. Total annual energy consumption in kWh, with automatic blinds (to avoid sunlight).

**CONCLUSIONS**

**Calibration data available and simulation model.**

The importance of achieving a calibrated model is crucial to adjust control systems to a significant potential of energy savings in existing buildings. But in general, it is very difficult to obtain reliable data in terms of quality and quantity (management and owners of buildings, user's activities, technical problems with measurement instruments, confidential data, predisposition from users to answer surveys, etc.)

The spot measurement and monitoring data are not extended and were made in punctual situation to calibrate an annual performance simulation. Moreover, the illuminance values simulated are much closer to measured data. Also, the 21/03 date was a good point to start the calibration process to achieve information, because equinox time is an intermediate seasonal point to calculate daylight availability.

### Simulation results

There are additional strategies to increase the use of natural light and visual comfort for example to achieve uniformity and provide daylight in deeper rooms, as a redirection daylighting system (eg; mirror, prismatic, anilodic systems, etc.)

Although many solutions of optimization and improvement systems in daylight were not taken into account for the realization of dynamic simulations in this project, the results allow summarizing the optimal control schemes to energy efficiency, as a power consumption reference. This allows translating the control schemes in mock-ups for testing their behaviour in real conditions.

### Control system

In a Mediterranean climate, a possible difficulty to maintain the visual comfort is that solar protection devices do not work or are not operated (by users or control systems) or these are not considered in the design, which may cause potential excessive solar gain or glare. Because of this, it is very important in this temperate sunny climate to consider control systems which can manage sunlight protection and regulation of daylight amounts. However, in this study, a solar shading device and daylight regulation system reduces the availability of daylight index (DA%, UDI%) and affects the total annual energy consumption in lighting (kWh).

### NOMENCLATURE

*DAYSIM* indexes:

DA% = Daylight Autonomy

DGP% = Daylight Glare Probability

UDI% = Useful Daylight Index %

UDI<sub>100-2000</sub> % = Useful Daylight Index % (horizontal illuminances range from 100 to 2000 lux)

UDI<sub>>2000</sub> % = Useful Daylight Index % (horizontal illuminances range up to 2000 lux, is considerar that can cuase glare problems)

### ACKNOWLEDGEMENT

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