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Daylighting and Energy Performance Evaluation of an Egg-Crate Device for Hospital Building Retrofitting in a Mediterranean Climate

Carmen María Calama-González *, Ángel Luis León-Rodríguez and Rafael Suárez

Instituto Universitario de Arquitectura y Ciencias de la Construcción, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla, Av. Reina Mercedes 2, 410012 Seville, Spain; leonr@us.es (Á.L.L.-R.); rsuarez@us.es (R.S.)

* Correspondence: ccalama@us.es; Tel.: +34-954-559-517

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Abstract: Hospital buildings present a significant savings potential in order to meet the objectives of H2020. The improvement of healthcare built environments contributes to improving the health of patients. In this respect, passive measurements must be prioritized, especially in relation to the weakest element of the building thermal enclosure: the window opening. Shading devices allow solar radiation and indoor temperature to be controlled, as well as improving visual comfort, mostly in buildings with a Mediterranean climate. This factor is of great importance when considering the increase in outdoor temperatures expected due to climate change. Unlike other studies in which predictive models are implemented, this paper examines a methodology based on the simultaneous monitoring of ambient variables, in real use and operative conditions, for two hospital rooms located in southern Spain. The aim of this research is to provide a comparative assessment of ambient conditions in a standard room with an egg-crate device and in a non-shaded one. The use of an egg-crate device allows a better yearly performance, improving natural illuminance levels, reducing incident solar radiation on the window, and decreasing artificial lighting consumption. However, its efficiency is greatly conditioned by the user patterns in relation to ambient systems, as the blind aperture level and the activation of the lighting system are directly controlled by users.

Keywords: hospital buildings; shading devices; solar radiation; daylight; illuminance; overheating; energy consumption; energy savings

1. Introduction

One of the priority action requirements established by the Energy Performance of Buidlings Directive (EPBD) [1] for the improvement of energy efficiency in buildings for H2020 is retrofitting the existing building stock, both housing and tertiary. Although there is extensive research of office and housing stock retrofitting, very few studies focus on hospital buildings. Hospitals are complex buildings, with numerous functional zones and different requirements. This implies an intricate decision-making process when these buildings have to be adapted in order to meet the current energy efficiency standards.

In the Mediterranean area, several individual studies have been carried out for the energy characterization and the evaluation of measures for energy efficiency improvement in hospital buildings [2]. Before using simulation models to their full potential, an application protocol must be designed for the methodology according to the building's typology, use, and occupation patterns, construction and monitoring data availability; climate zone; and so on [3]. Hospital buildings present a high savings potential [4], which can be focused on the energy efficiency improvement of heating, ventilation, and air-conditioning (HVAC) systems [5] or the use of LED lighting systems [6]. However, it is crucial to prioritize passive measures such as natural ventilation, daylighting, or shading [7]. Kolokotsa et al. [8] reported how implementing simple energy saving techniques could easily derive into savings of up to 10% of primary energy consumed. Moreover, measures taken ought to consider a new challenge; global warning, which leads to the development of a new line of research relating to the resilience to hospitals overheating, as in the case of public hospitals in the United Kingdom [9].

Considering the existing high levels of solar radiation in the Mediterranean area, initial intervention actions must focus on the element most vulnerable and sensitive to overheating problems, and thermal and visual discomfort: the window opening. Slatted shutters are frequently used as shading devices to block solar radiation in order to prevent glare and unwanted heat gain in patients' rooms in summer.

In addition to mitigating thermal gains, these elements also reduce natural illuminance, which is replaced by artificial lighting, prompting an increase in electrical consumption throughout most of the day. Nevertheless, it should be highlighted that natural lighting has specific qualities that cannot be provided by artificial lighting. The changing intensity of natural lighting, direction, time, and colour connect occupants with climate, season, and hour of day, contributing significantly to the wellbeing of patients [10].

Recent studies have revealed a correlation between the healthcare built environment and patients' health. This research highlights the positive effect of the built environment on the state of mind [11] and health outcomes of patients [12]. When considering the healing environment, several parameters relating to the window opening are outlined: daylight, which has an antidepressant effect on occupants [13]; and views through the windows, which relieve stress and shorten the length of patients' stays [14]. In particular, south- and west-facing windows are more vulnerable to overheating and thermal discomfort, along with a non-uniform distribution of daylight. An adequate design of the shading device reduces solar radiation and indoor temperature and improves visual comfort [15,16]. The design of shading devices must also take into consideration energy, lighting, and visual parameters, maintaining an appropriate level of indoor illuminance with minimum solar gains and promoting the reduction of energy consumption [17]. The optimal position for shading devices is usually outdoors, in front of the window, because indoor positions can even thermally worsen energy performance, increasing cooling energy consumption, as confirmed by Atzeri et al. [18]. Several authors have assessed different shading devices solutions [19], considering their performance in terms of energy savings, thermal comfort, and natural illuminance [20], mostly using simulation models [21]. However, in hospital buildings, these techniques come up against the problem of properly defining real operation conditions and use patterns. Given the complexity of this definition in this type of buildings, it must be supported by an adequate validation of the simulation models [22].

Stazi et al. [20] compared sliding perforated aluminium panels, horizontal aluminium shutters, and wooden slats, validating these as one of the most appropriate solutions. Freewan [23] observes the effect of external devices in an office building in Jordan: vertical and diagonal fins and egg-crate. Air temperature, illuminance level, and thermal and visual environment were monitored and compared with those of a non-shaded office. Yearly, egg-crate shading devices showed better performance, blocking sunlight in warm periods, but allowing its penetration in cold periods.

The main objective of this research is to evaluate the improvement of indoor comfort conditions of a hospital room in the Mediterranean climate, using an egg-crate device. To do so, two hospital rooms were simultaneously assessed by monitoring ambient conditions in real operation and use conditions. An egg-crate device was implemented in one of the rooms, while original conditions were maintained in the other. The influence of the egg-crate device over indoor illuminance (lux), solar radiation reaching the window (W/m^2), operative indoor temperatures (°C), and lighting consumption (kWh) was evaluated throughout a year. Future research will extend this analysis to other variables, as well as to the possibility of optimizing the shading device proposed.

2. Methodology

The methodology is based on the monitoring of ambient variables, in real use and operational conditions, for two hospital rooms in southern Spain.

One of the rooms has an egg-crate device in front of the window, while original conditions are maintained in the other. This configuration allowed the simultaneous evaluation of the influence of solar protections on ambient and energy variables under the same outdoor conditions, monitoring both rooms during a 12-month period. This study focused mainly on the evaluation of solar radiation levels, indoor natural illuminance, and electrical consumption of the lighting system. A descriptive statistical analysis was also carried out, using the Statistics Toolbox of the matrix software Matlab [24], which allows the comparison between variables considering similar illuminance levels, shutter aperture levels, and solar radiation.

2.1. Description of Case Study

The building analysed in this study is the Virgen Macarena University Hospital, a public general hospital built in 1974 and managed by the Regional Government of Andalusia (Spain). It is located in the city of Seville (Figure 1): latitude 37.25° N and longitude −5.60° W.

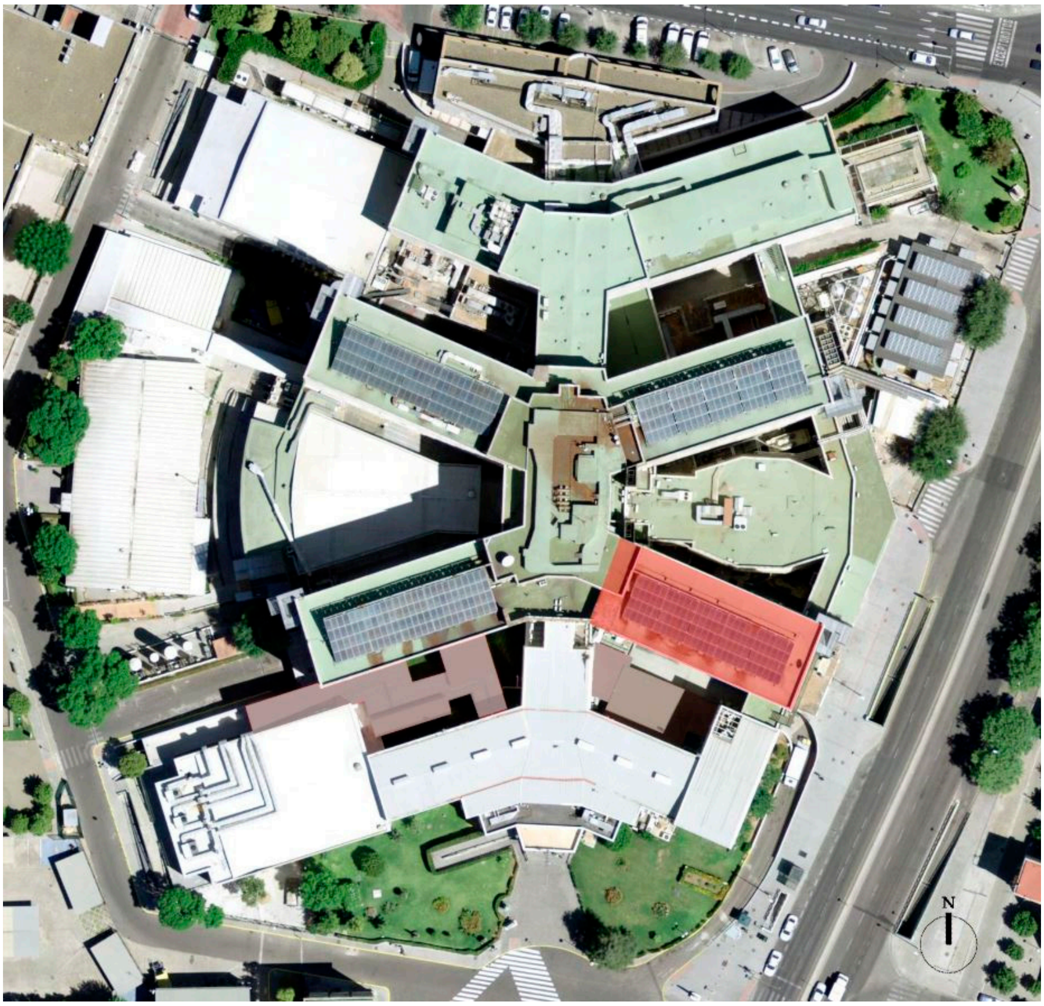


Figure 1. Image of the rooftop of the Virgen Macarena University Hospital (Seville). The southeast wing of the hospital, where the monitored rooms are located, is indicated in red. Base image: Google Earth Pro., 26 July 2017.

The two adjoining rooms monitored are located on the fifth floor of the southeast wing of the hospital (Figure 2). Constructive solutions and geometric dimensions are the same in both rooms. Their basic dimensions are 3.65 m width and 5.45 m depth, with a total useful area of 22.50 m^2 and a clearance height of 2.70 m (Figure 3). Another important fact is that each room has three patients' beds and a sofa for their companions.

(a)

(b)

Figure 2. (**a**) Virgen Macarena University Hospital. In the photograph, both monitored rooms have been marked in red colour: from left to right, the room without crate shading devices and the room with egg-crate shading devices; (**b**) indoor image of the room with egg-crate devices (room A).

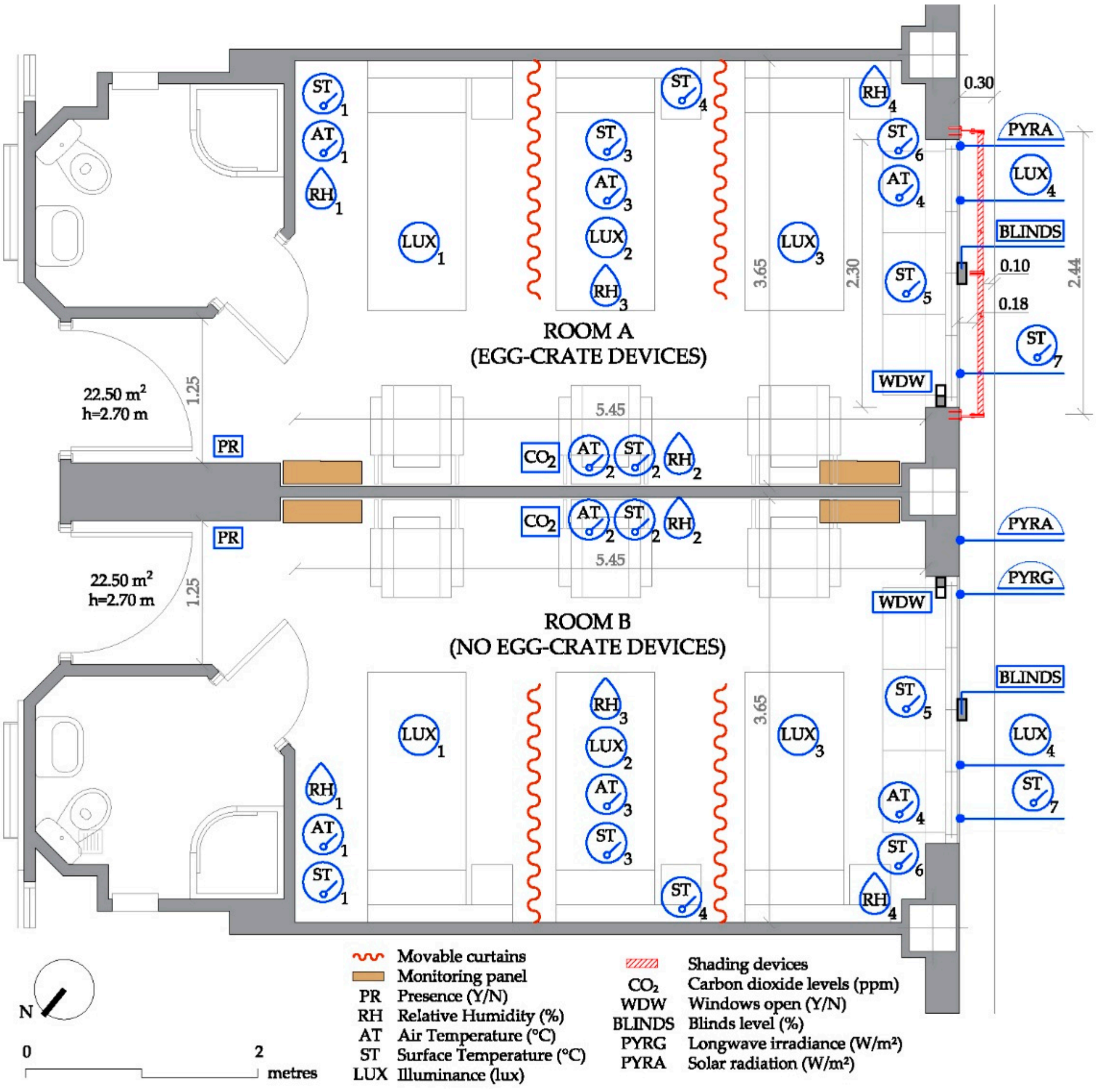


Figure 3. Floor plans of the rooms monitored with the location of the monitoring sensors.

Both rooms have a window 0.85-m high and 2.30-m wide, which represents almost 20% of the facade surface of each room. Windows are set back 0.30 m from the exterior facade line, making the lintel a continuous cantilever along the window openings. Each window is made up of two symmetrical aluminium sliding frames with a solar protection film over the external surface of the glass. The technical characteristics of the windows are shown in Table 1. These data have been obtained from the datasheets provided by the manufacturer Réflectiv [25].

Table 1. Technical characteristics of the windows.

Variable		Value
4/8/4 Double-Glazing, Metal Frame (No Thermal Bridge)		**Uo = 3.3 W/m^2·K**
Solar protection film (Réflectiv window film SOL 102)	Solar energy reflection	65%
	Solar energy absorption	24%
	Solar energy transmission	11%
	Visible light transmission	16%
	Visible light reflection	60%
	Solar energy rejected	79%
	UV-rays transmission	1%

The solar control and shading system of the rooms is made up of polyvinyl chloride (PVC) slatted shutters, with horizontal slats. These are all original elements of the building construction. Additionally, an external egg-crate device was implemented in one of the rooms (room A). Its configuration is described in detail in Section 2.2. In the other room (room B), the original state has been maintained.

The artificial lighting system is the same for both rooms. This system is made up of three linear luminaires with 18 W power fluorescent lamps, placed above the headboard of each bed. In addition, a down light with two low energy consumption 2 × 18 W lamps are found in the access area for the rooms. Each luminaire can be controlled individually.

Both rooms have a heating, ventilation, and air-conditioning (HVAC) system that uses outdoor air for indoor air quality. Each room has a duct type fan coil that partially overcomes thermal loads and runs continuously 24 h a day. This system is centrally controlled by hospital maintenance personnel and cannot be modified by users.

Finally, it should be noted that because of some measurement uncertainties in the analysis conducted, the following boundaries have been considered: (1) the analysis of results reports that both rooms are always occupied by patients. However, the hospital administration has been unable to provide any public records to confirm this and there is no control over patients' companions. Thus, we have no access to information on the actual number of occupants in the rooms; (2) hospital rooms have a movable curtain separating the beds, which are used whenever there is a need to ensure privacy for sanitary purposes. These curtains are not controlled by the monitoring system. Therefore, the real influence of these elements on natural illuminance levels cannot be measured precisely.

2.2. Shading Device Description

The solar protection system studied consists of a white methacrylate slat grid assembled to create a lattice with the window size. This element is designed and manufactured in the Digital Fabrication Laboratory of the Higher Technical School of Architecture of the University of Seville (FabLab), using a laser cutting machine.

Each slat is 3 mm thick and 45 mm deep. The solar protection grid, made up of 83 × 83 mm squares, is 180 mm from the solar protection and the window glass, which in turn is 100 mm from the external facade line.

For the purposes of assembly safety and mechanical security purposes, two auxiliary 45 × 10 mm metal structures in S235 JR corrosion-proof steel were installed, and separated by 45 × 5 mm metal anchorage. The sections mentioned link together forming two 1220 × 792.5 mm frames, and leaving two empty slots of 1205 × 760 mm where the 1200 × 755 mm lattices are placed (Figure 4).

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

Figure 4. Egg-crate device designed: (**a**) indoor view; (**b**) outdoor view.

2.3. Monitoring System

The monitoring system is integrated by a total of eight nodes or data loggers, recording information at 10-min intervals, following EN ISO 7726:2001 [26].

As can be seen in Figure 3, each room has two monitoring panels in which the hubs are located, with a total of four hubs per room.

The first hub measures the electrical consumption of the room's lighting system, recording voltage data, as well as information on power consumption and electricity intensity. The second hub records data from several monitoring sensors: a detection sensor, four air temperature sensors, four relative humidity sensors, a carbon dioxide detector, and four sensors that control the window opening (open/closed). The seven surface temperature sensors are connected to the third hub, while the fourth and final hub includes four lux meters (three indoors and one outdoors), a pyranometer (outdoor), a pyrgeometer (outdoor), and the sensor that measures the aperture level of blinds. Table 2 shows the main technical characteristics of the sensors used to monitor the rooms.

Table 2. Probes in the monitored rooms. Y/N—yes/no.

Device	#per room (Total)	Location	Unit	Range	Accuracy
Thermocouple	7 (14)	On surface: walls and ceiling	°C	−30, +350	±1 ± 0.75%
Thermometer	4 (8)	Interior matrix	°C	−40, +80	±0.2 °C (0–40 °C) ± 0.2 °C (40–80 °C)
Hygrometer	4 (8)	Interior matrix and outdoors	%	0–100	±1.5% (0–90%) ± 2.5% (90–100%)
Lux meter	4 (8)	Interior matrix and outdoors	lux	0–200,000	±4.0%
CO_2 detector	1 (2)	On surface: east wall	ppm	0–2000	±(40 ppm + 4.8% of reading)
Presence detector	1 (2)	North walls	Y/N	4–15 m	-
Window opening control	4 (8)	Windows	Y/N	-	-
Blind level sensor	1 (2)	Blinds	mm	200–8000	±25 mm
Pyranometer	1 (2)	Outdoor	W/m^2	0–4000	±2.0%
Pyrgeometer	1	Outdoor	W/m^2	−300, +100	±3.0% (−10, +40 °C)
Voltmeter	1 (2)	Electrical panel	V	-	-
Ammeter	1 (2)	Electrical panel	A	-	-
Potentiometer	1 (2)	Electrical panel	W	-	-
Energy	1 (2)	Electrical panel	kWh	-	-

Each room incorporates an outdoor pyranometer, placed in a vertical position and in parallel to the facade line. In order to evaluate the effectiveness of the solar protection studied, this device has been located behind the solar protection in room A. Meanwhile, the pyranometer in room B measures the global radiation that reaches the facade (without obstacles).

Data loggers regularly store information and every 30 min, data is uploaded to a file transfer protocol (FTP) server through a static IP using a mobile card. Furthermore, it is possible to download and/or modify the configuration of data using a simple remote access to the FTP server or an html portal. Prior to exporting data to the readable format of Microsoft Excel 2016® [27], information is processed and treated. This information has been interpreted and contrasted using the working tools of the multi-paradigm Matlab numerical software [24].

In order to complete outdoor ambient information, meteorological data is obtained from a local weather station 3.5 km from the hospital analysed. This weather station is located in the test cells managed by the research team itself [28] and measures the outdoor ambient conditions of air temperature, relative humidity, carbon dioxide levels, and wind velocity and direction at 5-min intervals. Table 3 below shows the characteristics of these devices.

Table 3. Probes in the weather station.

Device	#	Orientation	Unit	Range	Accuracy
Thermometer	2	N	°C	−40, +80	±0.15 ± 0.1%
Hygrometer	1	-	%	0–100	±3% (0.70%) ± 5% (71.10%)
CO_2 detector	1	-	Ppm	0–2000	±2.0%
Anemometer	1	-	m/s	0–50	±0.5
Vane	1	-	°	0–360	±2.5

2.4. Monitoring Periods Used in the Analysis of Results

Both rooms were monitored throughout a 12-month period (from May 2017 to April 2018) and this monitoring process continues to this day.

This paper analyses the first annual results obtained relating to solar radiation levels, indoor natural illuminance, and electrical consumption of the artificial lighting systems. To do so, three distinct periods were established: winter, mid-season (spring/autumn), and summer. Similar outdoor temperature ranges were grouped in order to classify the months of the year into these three periods. The characteristics of each period are indicated in Table 4.

Table 4. Characteristics of protocols analysed.

Periods	Description	T_{out} (°C)	Hours Analysed
Winter	1 December to 28 February	1.9–26.2	2159
Summer	1 June to 30 September	14.4–47.4	2927
Mid-Season	Rest of the year	5.2–38.2	3674

3. Analysis of Results

This section is dedicated to the analysis of the influence of the solar protections over the ambient and energy performance of the room with the egg-crate device (room A), compared with the one with no egg-crate device (room B). The results referring to solar radiation levels (W/m^2) and illuminance (lux) are presented, as well as those for electrical lighting consumption (kWh), distinguishing the winter period from the summer and mid-season. For the purposes of clarity in the figures introduced in this paper, and as no differences worth noticing were reported when compared with the measurement intervals, all the data analysed have been presented considering average hourly values. These have been determined from the 10-min interval considered for the variables monitored in the rooms and the 5-min interval in the case of the weather station. This decision helped reduce computational cost and calculation time.

3.1. Comparative Analysis of Solar Radiation and Illuminance Levels

The results of the descriptive statistical analysis are shown below. Table 5 indicates the percentage of hours (in relation to the total hours analysed in each period) in which a specific natural/artificial illuminance range is reached, as well as a given aperture of blinds and solar radiation level. In the natural illuminance analysis, only values equal to or above 10 klux are incorporated into the study. This decision means that it is only possible to consider conditions similar to clear sky, effectively ruling out night values, as well as cloudy sky conditions.

In winter, considering the total hours analysed, the percentage of hours with artificial lighting is 38.1% in the egg-crate room (room A), which implies 1336 h of natural illuminance. In contrast, the use of artificial lighting reaches 61.5% of the hours in the non egg-crate room (room B), which means that natural illuminance decreases to 830 h. In summer, the percentages of the use of artificial lighting are 45.6% in room A (with 1104 h of natural illuminance) and 50.4% in room B (with 1018 h of natural illuminance).

Table 5. Statistical analysis of the percentage of hours in which specific ranges of natural and artificial illuminance, blind aperture, and solar radiation level are reached.

		% Hours of Total Hours Analysed					
		Room A (Shading Devices)			Room B (No Shading Devices)		
Variables	**Ranges**	**Winter**	**Mid-Season**	**Summer**	**Winter**	**Mid-Season**	**Summer**
Natural Illuminance (lux)	<100	47.7	28.6	37.9	28.1	29.7	36.6
	$100 < L \leq 300$	10.9	8.9	7.2	6.8	11.8	10.4
	>300	3.3	2.7	0.5	3.6	4.9	2.6
Artificial Illuminance (lux)	All	38.1	59.8	45.6	61.5	53.6	50.4
Blind level (%)	≤25	25.2	18.0	19.0	7.6	11.8	21.5
	$25 < B \leq 50$	74.2	56.0	67.7	31.9	22.4	45.1
	$50 < B \leq 75$	0.6	24.2	13.3	34.0	46.5	23.1
	>75	0.0	1.8	0.0	26.5	19.3	10.3
Solar radiation (W/m^2)	≤200	83.7	80.4	87.9	78.0	71.7	71.6
	>200	16.3	19.6	12.1	22.0	28.3	28.4

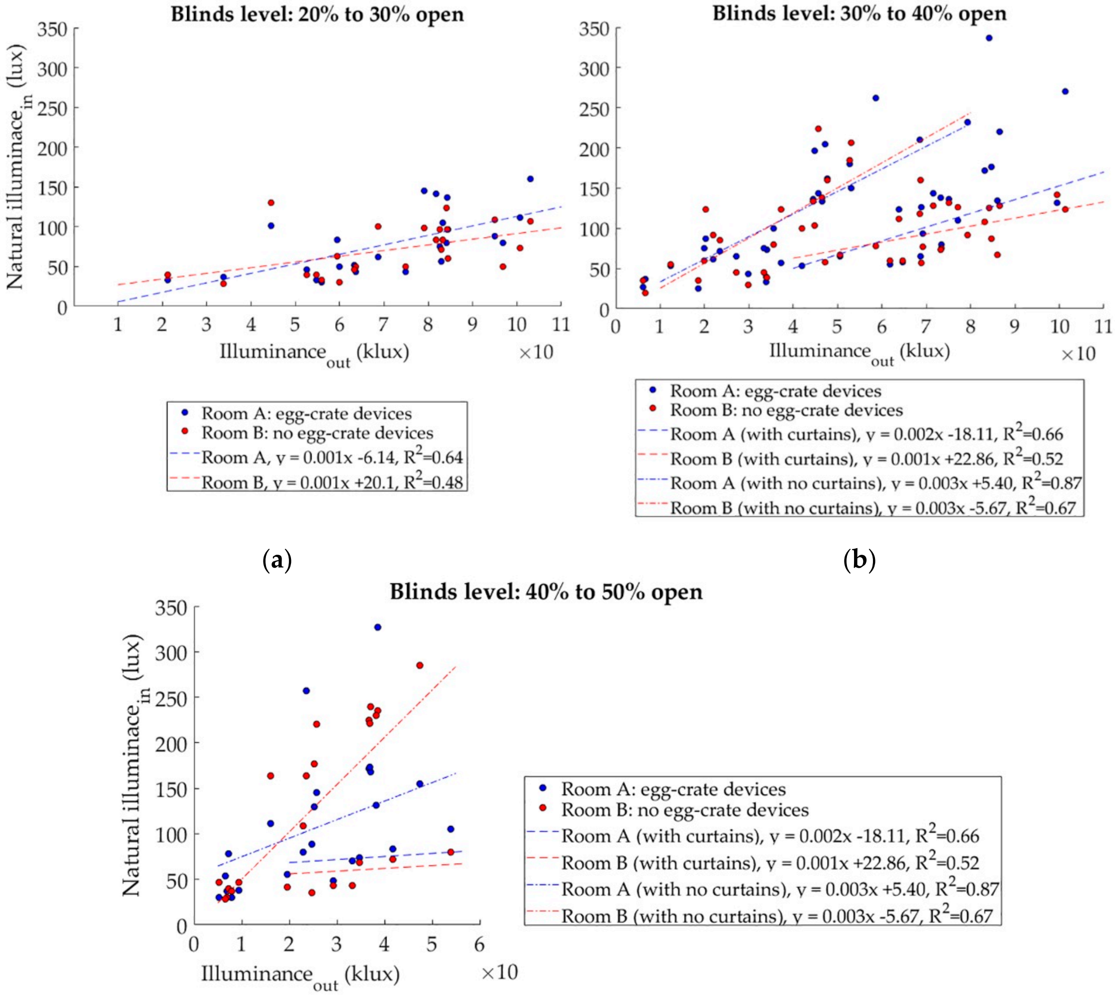
Note: Blind level of 100% means that blinds are fully open.

Logically, natural illuminance values in both rooms are greatly dependent on the aperture levels of the blind, which in turn are greatly conditioned by users. During the whole year, the aperture level of the blinds in winter in the room with egg-crate devices (room A) is between 25–50% during 74.2% of the total hours and during 56.0% of the hours in mid-season. Meanwhile, in the room without egg-crate devices (room B), blinds usually maintain higher aperture levels throughout the year. For instance, in winter, during 26.5% of the hours, the level of aperture of blinds in room B (no egg-crate devices) is above 75%, in comparison with the 0% level of the room A (egg-crate devices).

As observed in Table 5, the solar radiation levels that reach the window are over 200 W/m^2 during less than 20% of the hours analysed in the case of the room with egg-crate devices (room A). In room B, with no egg-crate devices, this percentage increases to almost 30% of the hours for summer and mid-season. In other words, in these periods, these solar protections manage to decrease the hours with solar radiation levels above 200 W/m^2 between 8% and 16%, respectively.

In Figure 5, hourly values of outdoor and indoor natural illuminance recorded in both rooms during the year are represented. For the sake of clarity and a greater control of noisy data, these results are classified according to different blind aperture levels: open between 20% and 30%, 30% and 40%, and 40% and 50%. The levels considered are the most frequently recorded during the year, as previously shown in Table 5. Moreover, the analysis of natural illuminance levels has been reduced to the values simultaneously recorded by the luxometers placed in the middle of both rooms. This decision allows the most representative values to be analysed, eliminating uncertainty deriving from the further measurement point, as the behaviour of patients' companions and the action of movable curtains are not controlled by the monitoring system. In this sense, measurements closer to the window have also been removed from this analysis, as specular behaviour caused by the grid has been observed.

For outdoor illuminance levels, only data recorded by the luxometer outside room B (no egg-crate devices and, therefore, no shading obstacles) have been considered, as the luxometer in room A is behind the egg-crate device.



(**c**)

Figure 5. Yearly natural illuminance levels in the room with egg-crate devices (room A) and in the room with no egg-crate devices (room B): (**a**) with blind aperture up to 25%; (**b**) with blind aperture between 25% and 50%; and (**c**) with blind aperture over 50%.

In the results, it can be observed that given the significant influence of users, there is no clear performance pattern. With blind aperture levels of 20–30%, indoor natural illuminance reaches similar values in both rooms. Indoor illuminance tendency shows a clear improvement in room A (egg-crate devices) with outdoor illuminance above 60,000 lux. When blind apertures of 30–40% are considered, two distinct tendencies can be observed, probably due to the influence of the individual curtains. In this case, natural illuminance is higher in room B (no egg-crate devices) when outdoor illuminance exceeds 40,000 lux. In contrast, indoor illuminance with curtains is higher in room A (egg-crate devices) with outdoor illuminance levels above 60,000 lux. This aspect is greatly significant in the last range analysed: 40–50%. In this case, indoor illuminance in room B (without egg-crate devices) is clearly higher when outdoor levels exceed 20,000 lux and without curtains. With curtains, room A maintains better indoor illuminance levels. The higher the blind aperture level, the lower the outdoor illuminance levels recorded.

In any case, daily reduction in the incident solar radiation that reaches the window of the room with egg-crate devices (room A) is very significant in periods with high outdoor temperatures. In winter (Figure 6), solar radiation decreases by 13–15% with the solar protections designed. However, there is usually an increase in solar radiation levels at noon due to the diffusivity of the solar protection film, which can occasionally further increase the solar radiation recorded (around 4–10%) in the room with egg-crate devices. This phenomenon is believed to be caused by the specular reflections of the grid itself, especially given the material used in its manufacturing. In summer (Figure 7), this reduction is somewhere in the region of 30% and 39%, compared with the room without egg-crate devices (room B). It has been found that solar radiation decreases by around 23–33% in the mid-season period.

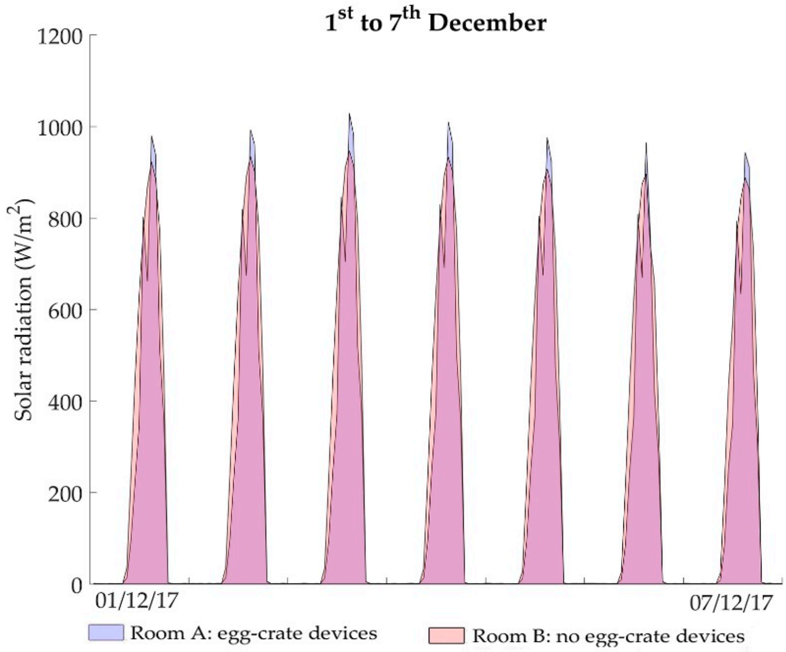


Figure 6. Solar radiation levels recorded from 1 to 7 December in the room with egg-crate devices (blue) and in the room with no egg-crate devices (red).

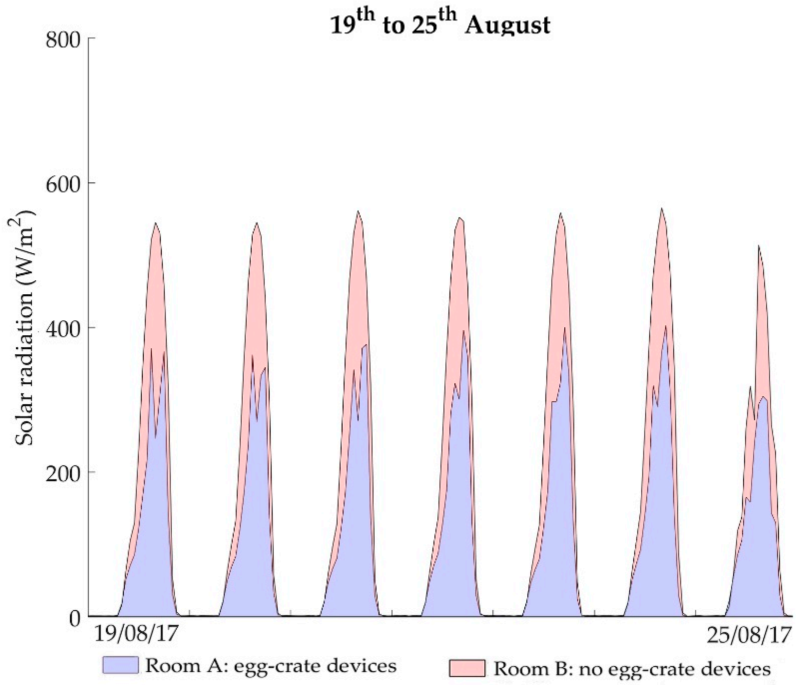


Figure 7. Solar radiation levels recorded from 19 to 25 August in the room with egg-crate devices (blue) and in the room with no egg-crate devices (red).

This solar radiation reduction due to the solar protections analysed should be reflected on the operative temperatures of the room in the case of free running conditions. However, as can be seen in Figures 8 and 9, the air-conditioning system in hospital rooms is permanently active and cannot be controlled by users, resulting in practically constant operative temperatures year-round in both rooms; with an average thermal range between 23 and 25 °C. In this case, slight deviations in temperature are a consequence of occasional variations in occupancy thermal loads.

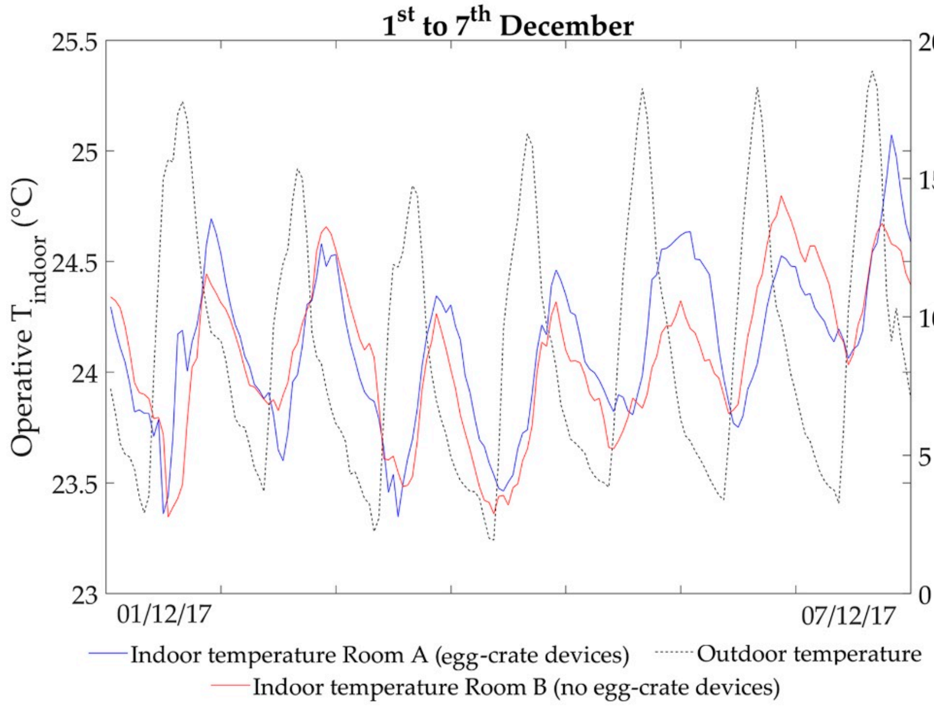


Figure 8. Outdoor and operative indoor temperatures from 1 to 7 December in both rooms.

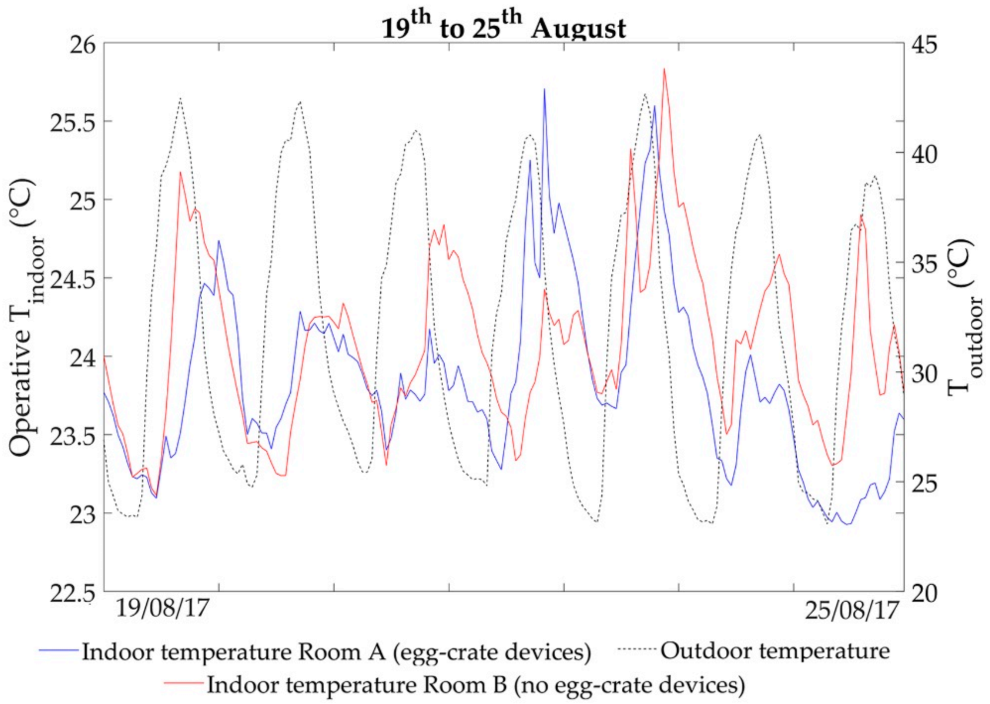


Figure 9. Outdoor and operative indoor temperatures from 19 to 25 August in both rooms.

3.2. Comparative Analysis of Lighting Consumption

Table 6 shows the percentage of total hours in which the artificial lighting system is active in both rooms, in relation to a certain range of blind apertures.

Table 6. Statistical analysis of the percentage of total hours in which artificial lighting systems are active, considering a specific blind aperture level.

Variables	% Hours of Total Hours Analysed					
	Room A (Shading Devices)			Room B (No Shading Devices)		
Lights on when	Winter	Mid-Season	Summer	Winter	Mid-Season	Summer
Blinds ≤25%	27.0	16.0	13.6	6.2	8.8	14.0
Blinds 25% < B ≤ 50%	71.7	58.5	68.4	30.2	20.9	49.5
Blinds 50% < B ≤ 75%	1.3	23.2	18.0	35.1	48.7	24.0
Blinds >75%	0.0	2.2	0.0	28.5	21.6	12.5

Note: Blind level of 100% means that blinds are fully open.

To obtain this data, only outdoor illuminance values above 10 klux have been considered. Thus, average hourly indoor daylight illuminance values recorded under conditions highly similar to clear sky have been represented. This also makes it possible to evaluate artificial lighting activation and consumption, excluding night values, from the analysis. In order to avoid confusion, values in this table have been established as percentages of the data filtered. These percentages were previously shown as artificial illuminance in Table 5.

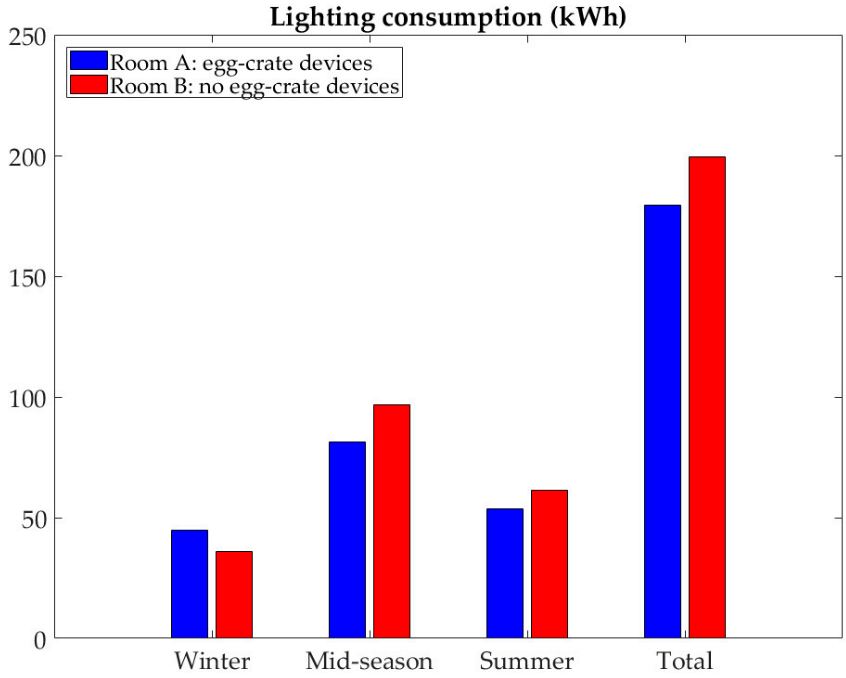
In room A with egg-crate devices, artificial lighting systems are mainly used with blind apertures between 25–50%. Meanwhile, in room B with no egg-crate devices, lighting systems are more frequently active with blind levels around 50–75%, except in summer.

Figure 10 reflects lighting consumption results in both rooms, for each period analysed, as well as the global value obtained for the whole year. The results show that the average cumulative lighting consumption is almost 20 kWh higher in the room with no egg-crate devices (room B) when compared with that with egg-crate devices (room A). Given that electricity depends on the energy structure of the country (Spain), there are reported CO_2 emission savings of around 12.98 $kgCO_2$ equivalent/kWh, considering an emission factor of 0.649 $kgCO_2$/kWh [29]. This means 10% of emission savings in the room with the egg-crate device.

It can also be seen that the solar protection system designed penalizes energy consumption by about 19.4% in winter. On the other hand, in the remaining periods, these solar protections allow energy savings of about 16.0% in mid-season and 12.7% in summer.

It should be taken into consideration that in room A, with egg-crate devices, the aperture level of blinds is between 25% and 50% during approximately 65% of the total hours. In contrast, the blind levels for room B, without egg-crate devices, are between 50% and 75% during the same period of time. The lighting system is active around 53.5% of the annual hours in room A, with egg-crate devices, compared with 55.6% of annual hours in room B, without egg-crate devices.

The mid-season period is particularly interesting, as despite recording a higher percentage of hours when the lighting system is on in room A (egg-crate devices), there is less cumulative lighting consumption. The reason for this is that the monitoring system only indicates the moment when at least one of the luminaires is turned on. Therefore, this could mean that there are more luminaires on during a lower percentage of hours in room B (no egg-crate devices), while there are fewer luminaires turned on in room A during a higher percentage of hours.



Variable	Room	Winter	Mid-season	Summer	Per Year
Lighting consumption (kWh)	Room A: egg-crate devices	44.7	81.3	53.6	179.6
	Room B: no egg-crate devices	36.0	96.8	61.4	199.4

Figure 10. Comparative data of annual lighting consumption in the room with egg-crate devices (blue) and in the room without egg-crate devices (red).

4. Conclusions

This paper has analysed the influence of a solar protection egg-crate device type installed in a hospital room in southern Spain. Its influence on indoor illuminance levels (lux), solar radiation that reaches the window (W/m^2), indoor operative temperatures (°C), and lighting consumption (kWh) have been analysed throughout an entire year. To do so, an adjacent room with the same characteristics was used for the purposes of reference, carrying out a simultaneous comparison of both rooms under the same outdoor climate conditions.

This research has been greatly conditioned by a set of uncertainties that define certain boundaries within the analysis: (1) Although results report that both rooms are always occupied, no information about the specific number of patients during the analysis has been provided by the hospital administration. Additionally, patients' companions are also uncontrolled. (2) There is no information on the frequency of use of the individual movable curtains between the beds, which are likely to significantly influence natural illuminance levels. (3) The monitoring system does not record individual lighting consumption data for each luminaire in these rooms, only global values are recorded. So there is no information regarding how many lamps are on simultaneously or for how long. (4) Blind aperture level is controlled by users and varies greatly from one room to the other. Moreover, aperture levels are usually quite low and artificial lighting system is in use practically half of the time. (5) The use of shading devices allows a reduction in solar radiation, which should be reflected in indoor temperatures. Nevertheless, this impact cannot be properly estimated in the case study since the HVAC system has been on, that is, since 24/7.

All of these aspects, and the understandable constraints of conducting this analysis in a public hospital building, greatly limit the range of action of this research. Despite these issues, the following aspects can be highlighted among the results obtained:

- The use of the egg-crate device designed has been proven to decrease annual electrical lighting consumption by approximately 10%, which, in terms of CO_2 emission savings, represents the equivalent of 12.98 $kgCO_2$ per kWh for electricity generated in Spain. In winter, this solar protection results in a penalization of 20% of electrical consumption, as the egg-crate device prevents natural illuminance from fully penetrating the room. However, this aspect is balanced out by the average reduction of 26.8% registered in summer and mid-season periods.
- Although there is no clear performance pattern at a 95% confidence level, given the uncontrolled intervention of users, it can be confirmed that annual average indoor illuminance levels due to natural lighting are higher in the room with egg-crate devices. This is most probably due to two reasons: (1) the lattice avoids most of the direct solar radiation, while enhancing diffuse radiation thanks to the multiple specular reflections that take place in its structure, improving the uniformity of indoor illuminance levels; (2) the use of this type of element decreases outdoor glare, contributing to a reduction in the use of blinds that block light radiation completely.
- In this research, a direct relation between blind aperture levels and the activation of artificial lighting systems has not been observed. Equally, given that this effect is highly conditioned by users, solid conclusions could not be reached regarding these variables. In addition, the presence of individual movable curtains between the hospital beds implies greater uncertainty in natural illuminance levels recorded in the rooms, because these elements are not controlled by the monitoring system.
- A highly significant reduction of incident solar radiation is achieved with this solar protection system, with maximum values of 39% in summer and 33% in mid-season, when compared with a room with no egg-crate devices. In contrast, there is also a slight reduction of solar radiation by up to 15% in winter.
- Decreasing solar radiation levels has a proportional benefit in the reduction of the thermal loads that have to be resolved by air-conditioning systems, as a result of the heat transmission through window openings in facades. This is crucial in mid-periods and, especially, in summer. Although the reduction of solar radiation in winter results in the opposite effect, it should be noted that energy savings of air-conditioning systems would be positive in global terms, especially when considering future prospects of rising temperatures due to climate change.
- As a starting point in this research, it should be borne in mind that the effect of the solar protection analysed is minimized thanks to the other existing solar protections; the continuous 0.30 m cantilever in the facade and the solar protection film on the external surface of the glazing. Had it not been for these two elements, the influence of the solar protection analysed would have been more significant.

Considering all these facts, future research analysis is needed to adequately analyse the influence of the egg-crate device on indoor natural illuminance and solar radiation levels, complementing the results of this paper.

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