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Experimental regression model to predict natural lighting levels and energy savings in buildings

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Abstract

This paper presents a model to estimate the values of natural lighting that can be registered in interior spaces with light pipes, as well as the savings percentage that may be obtained by using this technology.

The lighting data obtained with an experimental prototype on scale of a teaching space at the University of Córdoba - where light pipes have been introduced -, together with the irradiance data registered in the radiometric station of the Applied Physics Department (University of Córdoba), have allowed the development of a regression model among the levels of natural lighting, sun elevation, and global and diffuse solar irradiance. The phenomenon behaviour has been simulated for a year with this regression, which has resulted in large time intervals with natural lighting levels above the minimum threshold recommended for teaching spaces.

Key words

Energy efficiency, natural lighting, light pipes.

1. Introduction

Until the half of the 20th century, lighting had both a qualitative and a quantitative charge in the architecture of buildings. Nevertheless, a uniform lighting is preferred in the most modern buildings. Currently, due to this fact, closed buildings are constructed where natural lighting is replaced by artificial lighting,[1] thereby increasing the energy needs of buildings.

It is necessary, however, to reverse this trend since the proper utilization of natural lighting is a very remarkable measure to improve energy efficiency in buildings. As a matter of fact, this simple measure may entail significant energy savings - especially in those areas with a high number of daily hours of sunlight.

Despite this idea, there are many occasions where natural lighting is a resource not adequately exploited. There is a clear example in cities like Córdoba (Lat. 37,88ºN. Long. ,4,76ºW) where, according to data recorded in 2013, the daily average of sunlight hours is over 8h/day, with a maximum value of 12h/day in July. [2] A specific example of this lack of efficiency, generalizable to multiple teaching buildings, is Aulario Averroes at the University of Córdoba. The classrooms of this building have no source of natural lighting, despite supporting 11 teaching hours per day. Even though windows are the most common option to introduce natural lighting in teaching spaces, this is not a feasible solution in Aulario Averroes as it has adjoining classrooms. This distribution impedes the capture of natural lighting through the side walls of the classrooms, so that the ceiling would be the only means possible to introduce natural lighting.

In these circumstances, this paper presents the design, the implementation in a prototype, and the experimental evaluation of a natural lighting method with light pipes in the classrooms of Aulario Averroes, Campus of Rabanales, University of Córdoba (Spain). To design the proposed system, we have born in mind that the levels of lighting needed in an interior space depend on the activity to be done in it - and more specifically in our case: in teaching spaces the minimum level recommended is 300 lx. [3] Furthermore, we present a regression model to estimate the illuminance levels in the interior of the building from the levels of direct and global solar irradiance in the exterior and characteristic geometrical parameters related to the movement Earth-Sun. Finally, and according to this model, we have carried out an estimation of energy consumption savings derived from the potential implementation of this method of natural lighting.

2. Methods of natural lighting

The election of the method of natural lighting depends on several factors, namely: the climate, the surrounding buildings, the orientation of the building, the reflections, and the purpose of the building. All these factors determine the most efficient method of natural lighting.

Galleries, porches, patios, skylights and windows are the most common methods to introduce natural lighting to the interior of buildings. However, there are alternative methods, increasingly used, such as laser cut panels, zenith skylights, prismatic panels, corbels or light pipes [4].

A. Light pipes

Light pipes can be used to introduce natural lighting in interior spaces through the ceiling; thereby, in this study, we have chosen this technology.

Figure 1 shows the typical configuration of a light pipe. The upper end of these light pipes is placed on the roof or ceiling of a building so that solar radiation impinges on it. A dome in this upper end isolates the tube from dust particles and ultraviolet radiation [5], while it allows the entry of sunlight.

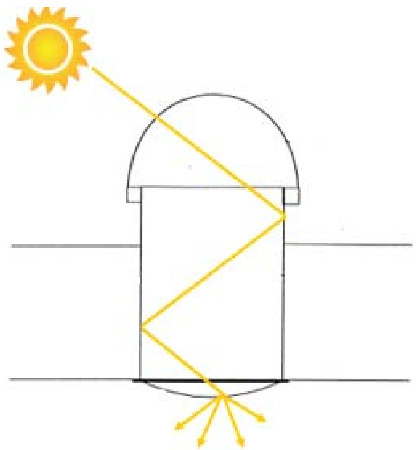

Fig. 1. Diagram of a standard light pipe.

Due to the high reflectivity of the material inside the pipe, the sunrays that enter through the dome go along the light pipe to the space to be illuminated thanks to multiple specular reflections. The transmission rate of the light pipes is approximately 95%, depending on the material used to build it. Finally, in its lower part, the light pipe has a diffuser to disperse this lighting in the interior space. The type of diffuser may vary depending on the requirements of the room. [6]

3. Methodology

A. Building an experimental prototype

To evaluate experimentally the technical solution chosen in this paper, so that we can study and observe the characterization of the interior of the classroom with light pipes, we have built an experimental prototype to a 1:25 scale of a classroom subject of this study (Aulario Averroes, University of Córdoba). The classrooms of this building are, as a general rule, rectangular. Moreover, they have multi-tier classroom settings with the students' desks, while the area of the board and the teacher's desk is in the lower part of the classroom.

The walls have been covered with photographs of the studied classroom, in order to have a more realistic prototype. These photographs have been treated with CamScanner (free software for Android platforms) to provide an adequate perspective. As a result, we could recreate completely the interior of the classroom with high fidelity, as shown in Figure 2, which presents a comparative between the real classroom (Figure 2.a) and the prototype built (Figure 2.b).

Finally, we have installed nine light pipes in the prototype. To reach a higher uniformity of lighting, and knowing the needs of the classroom, we have installed three light pipes in the lower part of the classroom, three light pipes in the middle part, and two in the higher part of the classroom. Furthermore, we have installed the last light pipe over the teacher's desk.

a. b.

Fig. 2. (a) Actual classroom. (b) Experimental prototype built.

B. Measurement system

Once the prototype was built, we installed a system of 10 lighting sensors to measure the values of natural lighting in the interior of the classroom. Together with these sensors, the circuit has a real time clock (RTC) and a SD module to record the data. All these devices are controlled with a free hardware Arduino board, with a high reliability and low-cost.

The sensors used in this study have been TSL 2561, with a measurement range from 0.1 to 40 000 lx. Because of the high number of sensors in this project, they have been connected to the Arduino board with an I^2C protocol.

Fig 3. shows the distribution of sensors in the classrooms. We installed three sensors in the lower part of the classroom, three sensors in the middle part, three in the higher part of the classroom, and one over the teacher's desk.

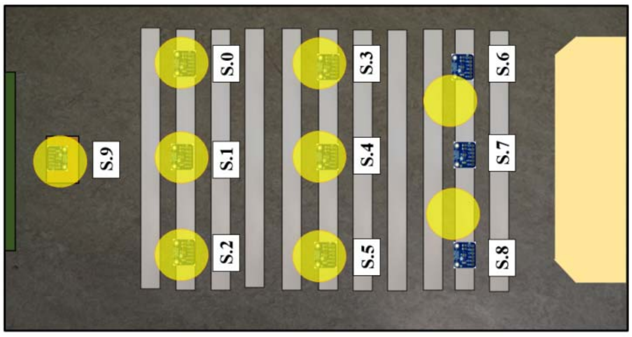

Figure 3. Diagram of the location of the light pipes and the sensors in the prototype.

C. Taking experimental data

To collect data for the study, the prototype was located with the same orientation of the real classroom at the radiometric station of the Applied Physics Department of the University of Córdoba, located at the rooftop of the Albert Einstein Building, close to Aulario Averroes.

Each sensor of the prototype recorded a value of average lighting every two minutes during the data collection phase. Simultaneously, the radiometric station - above mentioned - registered experimental measurements of global, diffuse, direct and inclined solar irradiance (W/m^2), as well as values of temperature (ºC), pressure (bar) and relative humidity. Finally, together with these values, we also studied the astronomical values of solar altitude and azimuth angle (deg).

It is important to highlight that the values were registered both on sunny and cloudy days during the data collection phase.

4. Results

A. Data analysis

Once the data were collected, we carried out the statistical analysis. Table 1 shows the mean, the maximum value and the typical deviation recorded by each sensor during the astronomical day.

Table 1. Statistical analysis of the 10 sensors.

Sensor nº	Average (lx)	Maximum value (lx)	Typical deviation (lx)
Sensor 0	138,3	491,49	95,42
Sensor 1	220,44	714,89	159,15
Sensor 2	125,14	430,92	85,19
Sensor 3	137,78	488,01	99,14
Sensor 4	273,79	1040,88	239,89
Sensor 5	118,87	427,97	82,39
Sensor 6	94,04	344,34	55,67
Sensor 7	66,32	212,74	50,86
Sensor 8	88,25	383,87	65,33
Sensor 9	110,56	450,63	80,21

It is observed that the sensors with a higher average lighting were 1 and 4 (220,44 and 273,79 lx, respectively). This is due to the fact that these sensors are located in the centre of the rows of the students' desks, so that they receive higher levels of lighting as they are surrounded by more light pipes. Sensor 7, even though it is a central sensor, receives lower levels of lighting than sensors 6 and 8, located at the ends of the same row. As can be seen in Figure 3, this is because this area of the classroom only has two light pipes.

Apart from being the sensor with the highest average value, sensor 6 registered the maximum lighting value during the whole period (1040.88 lx). This is also due to the location of the sensor.

Although no sensor exceeded in their average value 300 lx (minimum level recommended for teaching spaces) as shown below, there are time intervals in which this threshold is surpassed. Consequently, there are time intervals when the light pipes have sufficient capacity to meet the needs of the classroom, allowing energy savings

B. Cloudless day vs cloudy day

Below is given a comparative analysis of the system behaviour, both on cloudless and cloudy days.

Qualitative analysis

Figure 4 and Figure 5 show the appearance of the interior of the classroom, registered approximately at the same solar hour (12:42h and 12:48h) in two days with different weather conditions. As can be seen, the first case is a cloudless day, while the second is a cloudy day. When the sky is completely cloudless (Figure 4.a), there is good lighting in the interior of the classroom (Figure 4.b). However, on cloudy days (Figure 5.a), we can see that the levels of natural lighting are insufficient, so that a complementary artificial lighting system is needed (Figure 5.b).

Fig. 4. (a) Outdoor view on a cloudless. (b) Interior of the prototype on a cloudless.

Fig. 5. (a) Outdoor view on a cloudy day. (b) Interior of the prototype on a cloudy day.

Quantitative analysis

To perform a quantitative analysis of the behaviour of sunny and cloudy days, we represent graphically the evolution of the average lighting levels during the day in the different rows of desks with luxmeters. For this study, we have used the data corresponding to Figure 4 and Figure 5. Each of these curves has been obtained by calculating the mean of the three sensors of each row. In both figures, the horizontal green line represents the minimum recommended level. [3]

Figure 6 shows the evolution of lighting during a sunny day. Lighting values are recorded from 7:44h, they increase until 13:10h approximately, and after this moment, the levels decrease to become null at 19:18h.

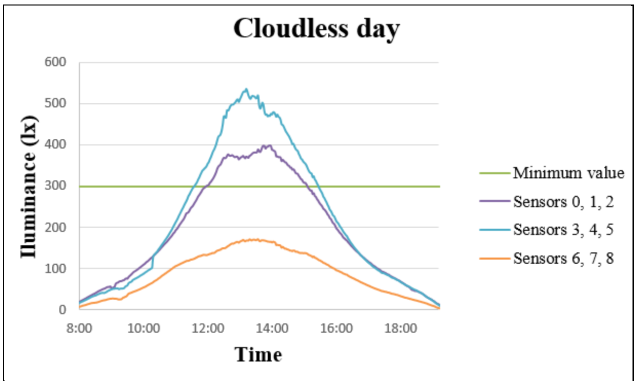

Fig .6. Evolution of lighting during a cloudless day.

From Figure 6 we conclude that the lower and middle areas of the classroom do not need any lighting system complementary to the natural lighting in certain hours of the day. This is due to the fact that, from 11:30h to 15:30h approximately, the minimum recommended threshold is surpassed in these areas.

Furthermore, Figure 7 shows similarly the evolution of lighting during a cloudy day. In this case, the first lighting values were registered at 8:04h, and the last values at 19:03h.

While Figure 6 shows a graph that increases and decreases homogeneously, Figure 7 shows jumps and spikes in lighting, corresponding to the instability of the weather conditions. Moreover, the values registered on the cloudy day are remarkably lower than on the sunny day.

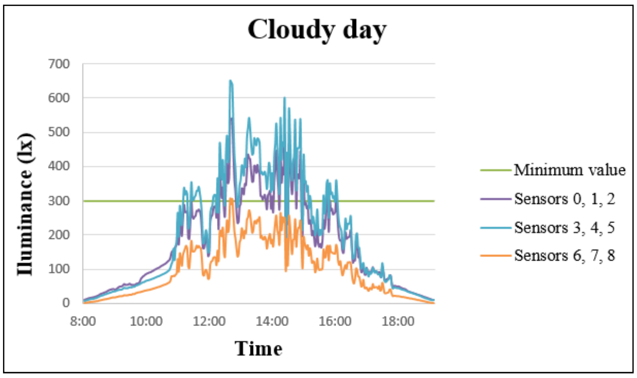

Fig .7. Evolution of lighting during a cloudy day.

C. Regression model

From the measurements recorded during the data collection, we developed a linear regression model to estimate, for any day or moment of the year, the average natural lighting that would be obtained in the three areas of the multi-tier classroom.

To carry out the regression model, we studied as input data values of solar azimuth angle, solar altitude (α), global solar irradiance (I_g), and direct and diffuse solar irradiance (I_D). While the azimuth angle and the solar altitude are astronomical values that can be calculated mathematically, the radiation values were collected from the radiometric station of the Applied Physics Department (UCO).

After analysing the level of significance of the different variables registered, we obtained the optimum regression model, shown in Eq. 1. This equation uses the values of solar altitude, solar altitude squared, global irradiance and diffuse irradiance. The values of the coefficients are shown in Table 2.

$$Ei\ mean = a\cdot\alpha + b\cdot\alpha^2 + c\cdot I_g + d\cdot I_D + e \qquad (1)$$
$$R^2 = 0{,}935$$

Table 2. Coefficients of the regression model.

	Coefficients
a	-2,01 (lx/º)
b	0,16 (lx/(º)^2)
c	-0,02 (m^2·lx/W)
d	0,25 (m^2·lx/W)
E	23,12 (lx)

D. Calculation of the savings percentage

From the regression model in Eq. 1, we can estimate the value of average lighting in the interior of the room for any time in which there are data of solar elevation, and global and diffuse irradiance.

Thereby, from experimental data of irradiance of 2013, we estimated - for the corresponding teaching calendar and timetable - the average lighting levels in the classroom if light pipes were installed. This data allowed the obtaining of a total of 95 896 instants when, being teaching hours, there were values of solar elevation, and global and diffuse irradiance.

Moreover, we measured with a luxmeter the real levels of average lighting with artificial lighting system existing in the real classroom, based on fluorescent lighting. These measures were collected in the equivalent locations where the prototype has the luxmeters installed. After this measurement, we obtained the average value of lighting in the classroom (493.33 lx), a value over the minimum threshold needed for teaching spaces. Figure 8 shows a frequency histogram in absolute lighting values in intervals of 50 lx for the year 2013.

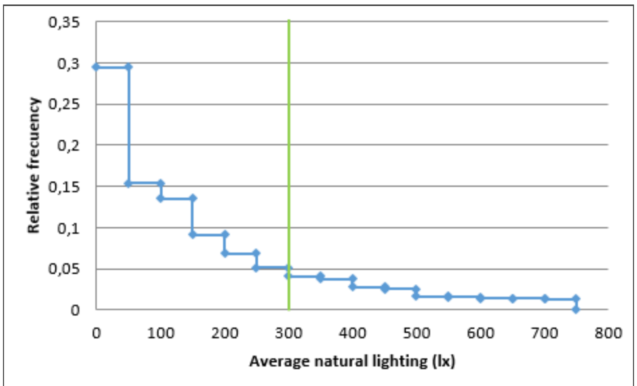

Fig. 8. Absolute frequencies of the estimated natural lighting in the classroom with light pipes for 2013.

To determine the savings percentage, we compared the natural lighting data with the recommended threshold value and the current artificial lighting of the classroom.

As a result, in the instants when the average natural lighting is over 300 lx, we can save 100 % of the current energy consumed. Thus, if we add in Figure 8 the instants (in percentages) when the average natural lighting is over 300 lx, we observe that the natural lighting system proposed here would be enough to illuminate adequately the classroom in 25.67% of the teaching instants in which the artificial lighting system is currently on.

Furthermore, when the average natural lighting does not exceed 300 lx, it is necessary to have an alternative, regulated artificial lighting system. This system, which combines natural and artificial lighting, may entail annual savings of 68.16% compared to the current consumption.

5. Conclusions

Despite the sun is the most abundant energy resource in Earth, it is not always used efficiently. Many of the buildings surrounding us every day are not designed to take advantage of the sunlight.

In this paper, we present the design of a natural lighting system for a teaching space based on light pipes, which may be extrapolated to other teaching buildings. Moreover, with the development of a regression model, we have managed to estimate the natural lighting levels that this system would provide for any instant of time, from the values of global solar irradiance, diffuse solar irradiance and solar altitude.

From this model, we have calculated the lighting levels in a teaching space of Aulario Averroes, at University of Córdoba. We have estimated, from the data obtained, that the installation of a combined system of natural lighting with light pipes, complemented with a regulated artificial lighting system, would entail energy savings of 68.16%.

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