Optimized management of lighting conditions in spaces with multiple users

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June 2017

Abstract

Electrical consumption has an increasing weight in society. Using responsibly is a concern due to consumption of fossil fuels. The biggest energetic consumption derives from buildings, and from these, a significant consumption is from electrical lighting. As such, a step to reduce electrical consumption is to use sunlight. Besides providing illumination to the room in question, it also allows the reduction of use of cooling systems, as there is less heat generated through electrical lighting due to heat gains in summer; in winter, the sunlight heats the surrounding space, reducing likewise the use of cooling systems and therefore the electrical consumption. Having a space well lit can increase the productivity of several users that are working in the space, however, it is necessary to take into account direct sunlight hitting the users, causing discomfort and glare. Rises then a problem, in which is necessary to use sunlight, whenever possible, that provides favorable conditions to work, without glare. This work has to measure efficiently the illumination and manage the control of the blinds and electrical lighting to provide a good working environment for the users. It was also made a study about the illuminance throughout the day to understand it's behavior and distribution. Finally, after the measure of illuminance, it is determined if it is necessary the use of the blinds to lower or rise the illuminance through the room, or use the electrical lighting in case the illuminance is not high enough.
Keywords: Automatic control, electrical consumption, illuminance model, illuminance optimization

1. Introduction

1.1. Background

Interior lighting in space offices accounts for approximately 25−35% of electricity used in buildings. Using daylight could reduce electrical consumption, and may help creating a better indoor environment. A higher indoor environment may increase visual comfort and rise the productivity of office users, and may reduce the need to use cooling systems, because there are less heat generated through electric lighting (usually called internal gains). All these factors help to reduce carbon footprint, which is a key point in today's society [10, 12].

However, in an office space, it is also important to take into account glare and direct sunlight, which causes visual discomfort to the users. To avoid these issues, shading devices are a necessary solution. These devices can block or allow direct sunlight, depending on the season and hour, block or enable solar gains (during cooling season, it is necessary to block direct sunlight to reduce the load on cooling systems, while in heating season, it is necessary to allow direct sunlight and thus to have solar gains, which in turn reduce the load in heating systems), can diffuse direct sunlight from clear skies (not causing visual discomfort) or transmit direct sunlight in overcast days [11, 2, 4]. There are two ways to control these shading devices: with manual or automatic control. Automatic control is a more attractive option, as it can monitor and control several devices at the same time, whatever is the space of the office, while with manual control it is only possible to control one system at the time, and it may not be optimal.

When natural lighting is not enough to ensure visual comfort, it is necessary to use artificial lighting systems. These can also be manually or automatically controlled. Automatic controlled lighting systems can substantially reduce the energy consumption on an office space using different methods. These systems are divided in three types: timers, daylight linked controls, and occupancy based controls. As the name suggests, timers turn light on/off during a specific time. Daylight controls, besides controlling on and off, can also regulate the dimming of lights, taking as input the illuminance of indoor lighting. Occupancy based controls can control lights depending if occupancy sensors detect someone [12].

As such, knowing how to control shading devices and artificial lighting systems, and thus obtaining energetic savings becomes of utmost importance. This document will provide an overview of how to control lighting systems (shading, artificial, etc) and how it impacts the illuminance measured, and the control made to guarantee that the illuminance in a given room is always within the comfort range for its users.

1.2. Energy consumption

When analyzing the energy consumption in 2014, for EU-28 [7], there are three categories that amounted to 83.9% of all energy: transport, which used 353 Mtoe or 33.2%; industry, responsible for 275 Mtoe, meaning 25.9% of all energy; and households, using 264 Mtoe or 24.8%, as it is possible to see from Fig. 1.

For Portugal, in regards to the same year [7], the distribution of electrical demand alone is slightly different. From the figure it is possible to see that most of energy used is for industry, consuming 17.304 $\times 10^9$ kWh, amounting a total of 34.47% of energy used, followed by the use in domestic (11.907 $\times 10^9$ kWh – 25.79%) and non-domestic (12.136 $\times 10^9$ kWh – 26.28%). Typically, the use of energy in buildings is mostly to electrical lighting, heating and cooling system (HVAC – heating, ventilation and air conditioning), and other electrical equipment (as computers, printers, etc.).

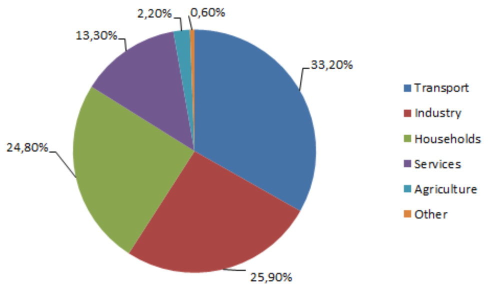


Figure 1: Energy consumption in EU-28 in 2014 [7].

1.3. Document layout

This document is organized as follows:

•In Chapter 2 is described some work and studies that were made in the area of interest.

•In Chapter 3 an overview of the methodology used.

•In Chapter 4 the results obtained are presented.

•In Chapter 5 a conclusion is drawn, describing all the achievements and pointing out suggestions for future work.

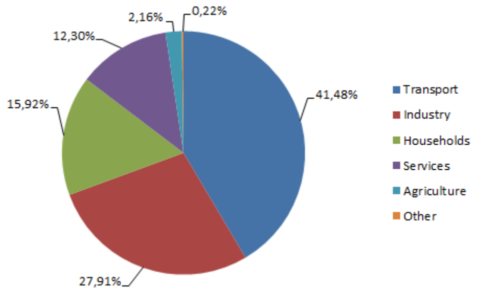


Figure 2: Energy consumption in Portugal in 2014 [7].

1.4. Solar Angles and Definitions

Due to the movement the Earth does around the Sun, and as well it's rotation along it's axis, there are some variables and angles which are important to define and are fundamental to this work [6]:

Latitude (ϕ). It is defined as the angle between the place in question and the equator, and is defined as $-90° \leq \phi \leq 90°$, where it is defined as positive the locations above the equator line (90° being the North Pole).

Declination (δ). It is the angle the sun makes at solar noon, measured with the plane of the equator. It can be calculated using the formula

$$\delta = 23.45 \times \sin\left(360 \times \frac{284 + \mathrm{n_{day}}}{365}\right), \quad (1)$$

where $\mathrm{n_{day}}$ represents the number of the day of the year.

Slope (β). This represents the angle between the plane of the surface and the horizontal, and has values between $0° \leq \beta \leq 180°$ (when $\beta > 90°$, then the slope is facing downward).

Angle of incidence (θ). Is the angle the light makes between a surface and it's normal.

$$\begin{aligned}\cos\theta = &\sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\gamma + \\ &\cos\delta\cos\phi\cos\beta\cos\omega + \cos\delta\sin\phi\sin\beta \cdot \\ &\cos\gamma\cos\omega + \cos\delta\sin\beta\sin\gamma\sin\omega\end{aligned} \quad (2)$$

Surface azimuth angle (γ). Making a projection of the surface on a horizontal plane, it is the angle between the projection and the normal of the surface. It has values between $-180° < \gamma < 180°$, where if the surface is facing south, the value is 0, if facing east is negative ($\gamma = -180°$), and positive if facing west ($\gamma = 180°$).

Hour angle (ω) . This value is due to the rotation the earth makes around the sun, giving a variation of 15° per hour to east or west of the local meridian. In the morning this value is negative, at noon is zero, and at the afternoon the value is positive. This value can be calculated using the following expression

$$\omega = 15 \times (t_s - 12), \qquad (3)$$

where t_s is the solar time.

1.5. Interior Lighting

To allow the quantification of light and to better understand it, it is necessary to define additional concepts, such as:

Illuminance (E). This value is a ratio between the luminous flux (ϕ) and a surface of area A in which the light hits, and is measured using lux (lx). This unit represents the measurement of the light's intensity, as perceived by the human eye. As such, illuminance can be computed using

$$E = \frac{\phi}{A}. \qquad [\text{lx}] \quad (4)$$

Luminance (L). This is the luminous flux reflected by a surface of reflectance ρ in a given direction. This represents the perception the human eye has if the surface is well lit or not, and it's unit is candela by square meter [cd/m^2]. In Fig. 3 is represented both illuminance and luminance.

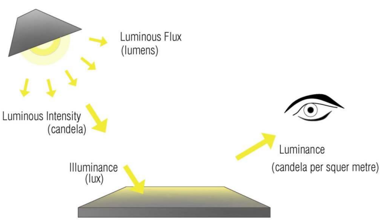


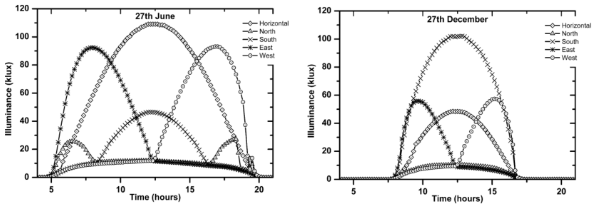
Figure 3: Representation of illuminance and luminance.

2. State-of-art

2.1. Direct and diffuse light

The sun emits electromagnetic radiation, which spawns from X-rays to radio waves. However, from that range, the most that reaches the surface of the Earth is visible light. Direct light is light that shines directly on a surface, while diffuse light is light that is overall homogenous, due to the reflections of light in other materials. The first type of light is characteristic of sunny days, and the second type is characteristic of overcast days. Because the days are different between each other, the quantity and type of light that reaches a specific place may vary. With a clear sky (generally with no clouds), and with plenty of direct sunlight, the illuminance measured will be high; on the other hand, with an overcast day (clouds covering the sky) and with diffuse sunlight, the illuminance measured will be much lower.

It has been studied the daylight illuminance measured in horizontal and vertical surfaces in a region in Spain [9]. The sensors were placed on a flat platform at a certain height, to avoid shading from the vegetation. The measures were made on clear days, during one year. Some of the obtained results are presented in Fig. 4.



(a) Summer (b) Winter

Figure 4: Illuminance measured in two clear days during summer and winter [9].

From Fig. 4 it is possible to see some interesting aspects. For one, the illuminances detected in North, East, South and West orientations are not equal throughout the day. For the sensors turned to East, the peak of illuminance is measured in the morning, while the sensor oriented to West has its peak in the afternoon, and this is verified all year long, as they are the part of day where it hits direct sunlight. For the rest of they day, the type of radiation the sensors measure is diffuse sunlight.

It is possible to conclude that the orientation of a sensor (and therefore a window) plays an important role in how much the sun light can be measured or how much can enter the room, and must be taken in consideration in the type of algorithm one wishes to use daylight to control electrical consumption from indoor lighting and heating/cooling systems [4].

2.2. Automatic control systems

Energy consumption for lighting in office spaces depends greatly of the space in which the office is located and also automatic control systems. With simple automatic control systems (as timers), there will be times of day where lights will be on, even though there is a possibility that there is no one using the space. This will cause an unnecessary consumption of energy, and the opposite can occur, where the lights turn off while there are users still in the space. On the other hand, with more robust control systems (like occupancy-based controls), it is possible to have as little energy consumption as possible, since when it detects a user, it turns on the lights; when the user leaves, the lights turn off.

This, however, raises a problem: the system may (or may not) detect a user, causing to turn the lights on/off incorrectly. It is also possible to control the intensity of light bulbs using daylight control systems. Using the daylight outside the office, these systems can dim the lights inside to adjust luminosity and thus be in range for user's visual comfort [12, 3].

A study measured data in office spaces [1]. In the first phase, it was monitored the lighting system, which users would control manually. This was done so to determine and evaluate the electric consumption related to the lighting systems. The user's behavior and their response were recorded in order to analyze the lighting conditions in the offices due to the use of electric lighting. After this, the next phase took place and was considerably longer than the first one, as it consisted in installing and calibrating a new automatic lighting system, using the user's requirements. In this second monitoring, the lighting control system was operated using automatic and manual control, and it's objective was to check if the lighting control system was working as intended and to see it's efficiency in providing energy savings and sufficient lighting conditions.

The data was recorded over a year, which included the horizontal illuminance of a desk, the illuminance estimated by the sensor, the percentage of dimming for each luminaire, and the electric energy consumption. The illuminance measured on the work planes was compared with target values which were defined before: when the lighting system was controlled manually, the target value was defined as 500 lx, while when the system was controlled automatically, the target value was defined for each of the offices, taking into account the requirements of the occupants. It is important to note that the values were measured in different time periods, and as such, comparisons and conclusions must take into account the different type of weather and external conditions.

From Fig. 5, it is possible to see that using manual control, it was verified the illuminance measured in a desk (750 lx) was often and substantially higher than the recommended value (500 lx). This can be explained as it is impossible to control the lighting system as a function of daylight; either it is on or off, and the system is controlled by the users. However, using automatic coupled with manual control, the illuminance measured drastically decreased (to about 400 lx) and became much closer to recommended value, as the lamps could be dimmed automatically.

Combining shading with automatic control generally gives the highest energy saving results, as it was studied in [8]. For example, having a system controlling the blinds position coupled with an

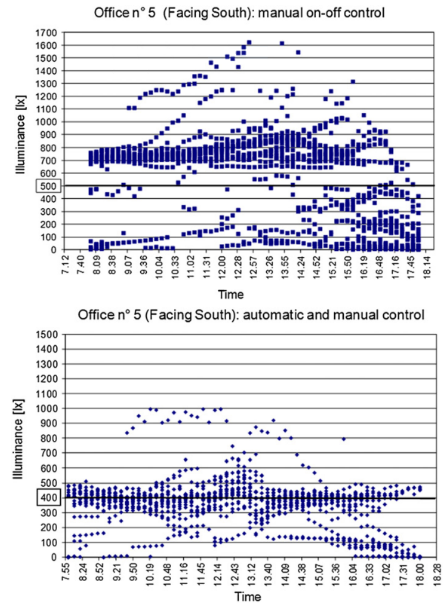


Figure 5: Illuminance measured with manual and automatic control (adapted from [1]).

occupancy-based detector allows the control of the blinds, opening them when a user isn't detected in a room, thus heating the room (due to high solar gains) and reducing the load of heating systems. When, on the other hand, the user is detected, the blinds close, for glare considerations and to cool the room, reducing the need to use cooling systems. If necessary, it can be used artificial lighting in case there is a risk to cause glare to the user if the blinds were open.

This system takes as inputs season, direct outside horizontal illuminance, inside and outside temperature, among others, and optimizes the system to compute the most comfortable setting. The optimization is done each night, with the objective to look for the most efficient set of parameters. This is done using a genetic algorithm, and applying small variations to the current controller. This setup shows the differences between two automatic controllers, one well-adjusted to the space and a conventional controller (on/off switch). The well-adjusted controller managed to control the heating power and the lighting system whether there was a user using the room or not, and also managed to avoid overheating the room. Using this setup, it has been possible to achieve 25% energy savings in comparison with a conventional controller [8]. However, one problem raised by this controller is the fact that it does not take into account the user's wishes. For instance, if the user changes the position of the blind, the system holds that position for a time set period, and then changes to the optimal one.

It is important, however, to have in consideration the space in which it is intended to optimize lighting. There are external factors (such as shading and orientation) that can influence indoor lighting, but there are as well indoor factors, such as the lifetime of lamps.

3. Methodology

This chapter presents and explain the method used for this work. The model is divided in three parts: the first one, involves using the Pèrez model, for the computation of solar radiation in a given point; the second one, is using the transmittance of classroom's window, calculated using values measured with two sensors, and with that determine how much solar radiation enters the room; the third one, is using an algorithm to determine the distribution of illuminance in the room, using a conversion between radiation and luxs.

The room in which will be studied the illuminance is the classroom V1.10, located in Pavilhão de Civil, in Instituto Superior Técnico. The classroom is located in the first floor, and is turned to East, meaning the peak of illuminance will be measured during the morning, while in the afternoon will be mostly from diffuse light.

3.1. Calibration of sensors

To measure the illuminance of the room, it was used two sensors from Adafruit®. The sensors were TSL2591, which could measure the illuminance instantaneously and could also take measurements within a set period the user could define previously. The sensors had different types of gain, as well as different times of integration. The gain of the sensors had a range of 1, ideal for situations with plenty of sunlight, until the maximum of 9876, which was indicated for situations with extremely low light. Apart from that, the sensor performed an integration of the values measured, and it ranged from 100 ms, again for situations with bright light, up until 600 ms, typical for environments with low light, as the higher the integration time, the more light the sensor is able to integrate, being more sensible to low light. The sensors were used with a gain of 1, as it would be hit by direct sunlight, and any gain would saturate the sensor, and an integration time of 100 ms, being the lowest, again for the same reason.

For the calibration of the sensors, it was used a light meter ISO-TECH 1332A. The light meter was placed alongside the Adafruit's sensors, and the values measured were then compared. The light meter has a resolution of 0.1 lux, and has an accuracy of ±3% for values measured below 10,000 lux. The light meter was calibrated to a standard incandescent lamp at color temperature of 2856 K. The spectral sensitivity characteristic is very close to the C.I.E. (International Commission of Illumination) photopic curve, which is displayed in figure 6.

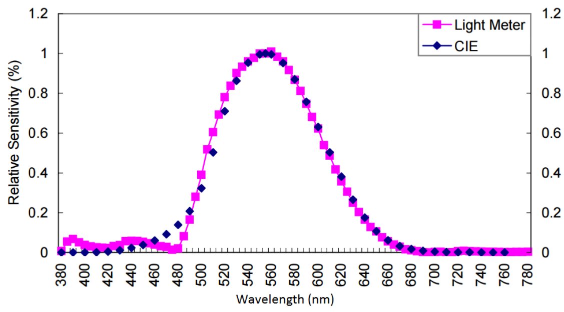


Figure 6: Characteristic of light meter ISO-TECH 1332A.

Using the values from both types of sensors (Adafruit's and the light meter) measured near the window, it is possible to determine a relation. As such, the result obtained between the two is in Fig. 7, using a linear function. The resulting fit allows a conversion from a measurement using an Adafruit sensor to illuminance in the region. It is important to note the slight dip near the region of 2,000 lux measured by the light meter. This is due to the working range of the light meter, as one of its range is 2,000. When one switches to another working range (the next one being 20,000 lux), the values near 2,000 are measured lower than with the previous range.

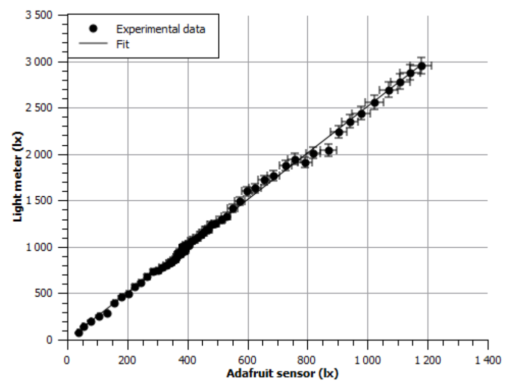


Figure 7: Relation between sensors and light meter.

The values obtain for a linear function used to fit the data is in table 1.

a	b	χ^2_{red}	R^2
2.510 ± 0.001	1.017 ± 7.145	9.356×10^2	0.997

Table 1: Parameters obtained for the fit between sensors and light meter.

3.2. Daylight control

To control the amount of sunlight (and thus illuminance) that enters the room, it is necessary to have blinds and/or electrical lighting. Having blinds allows to control the amount of direct sunlight, and prevent glare that users may experience. However, if the illuminance measured in the space is not sufficient to ensure work in comfortable conditions, then electrical lighting might be needed to raise the lighting conditions. Both can be used (for example, where the sunlight is too strong but isn't high enough when the blinds are open) to ensure the most comfortable conditions to the users. However, it is important to note that this solution increases the electrical consumption of the building.

The blinds can be controlled using a manual switch located near the window, which anyone can use, to adjust to the preferred light level. The blinds, when closing, close from the top and descend to the base of the window. When totally closed, and if one wishes to open them, the top third of the blinds rotate, being horizontal, and then the rest of the blinds follow, being completely horizontal. After this, they begin to rise, until the top.

4. Results

In this chapter the results obtained will be presented. Firstly will be presented the results for the prediction of the lighting in the room using a ratio between radiation and illuminance, the transmittance determined for the window in the room using the sensors, and the distribution of illuminance in the room. A threshold was defined for comfortable levels of illuminance to the users, and depending of the value predicted, a control method is applied to bring the illuminance to that range.

4.1. Radiation to lux conversion

With the values from Pèrez's model and the values measured from IST's meteorological station, it is possible to estimate the radiation that hits a horizontal plane. Likewise, with the values measured from Arduino®'s sensors, it is possible to know the illuminance in two points in the room. From this, it can be done a simple relation between incident radiation and illuminance outside the room. This allows to give an estimate and it is not necessary to permanently use a sensor to measure the illuminance.

This conversion is made over the values measured experimentally. As such, the results obtained could only be used for this location, as for different locations (different latitude and longitude), the radiation that hits produces different values of illuminance, as the angle of incidence of the sun is different.

Using the values measured from the meteorological station located in Instituto Superior Técnico, and the values measured from the Adafruit's sensors, for the same time, it was then compared. From those values, a relation from radiation and luxs was then determined, using different approaches.

Firstly, it was attempted an average between all the values, from morning until early afternoon (defined as all day). However, the difference between calculated values and experimental data was high. Afterwords, the data was split into two categories: the first one, included all the values measured during the morning, which was when sunlight was hitting the sensors directly; the second one, included the values which was measured with diffuse light (called split average). The point in which the division was made is after 12h17m28s, local time. It was also used values determined in Italy for the brightness coefficient for Pèrez anisotropic sky, to see if it could predict the illuminance in the room without a high error [5].

After calculating the ratios, it was then computed the prediction of illuminance in the room. For this computation, it was used the radiation measured from meteoIST, and divided by the ratio previously calculated. This value was then compared to the value measured with the sensors, to see the difference between the two. This would give an indication if the value was close to the value perceived in the room or not.

A visualization of the values obtained using different ratios is represented in Fig. 8. By making an average taking into account all the values recorded during a day will have the values with the highest difference between values predicted and values measured. This can be easily explained as the type of radiation that hits the sensors is different, that is, in the morning the prevailing type of radiation is direct (in this specific case), while in the afternoon there will only be diffuse radiation. As such, the value obtained when the average is being made includes both types, thus having higher difference; the error determined to this ratio can be as high as 550%. Using the value obtained for a location in Italy, it can be seen that the absolute values predicted are higher, even higher than the values recorded, meaning it over-estimates the values measured. The errors measured for this ratio do not fluctuate much; even though they are high, they range from 30% to about 85% for direct sunlight, and are at around 95% for diffuse sunlight. Finally, for the split average, there is a single point which has a high difference (the point at 10h57m29s) but overall it predicts the illuminance with an error lower than 40%. This ratio is the ration which could potentially have the best results, as the ratio would depend whether direct sunlight hit the room or not. As such, of the three methods, it is the one which has the lowest errors for the direct sunlight. For the diffuse component, it behaves in the same manner.

However, this raises an important dilemma. It isn't relevant to have high accuracy at high levels of illuminance because at that point the users will be uncomfortable due to glare and direct sunlight. As such, having a high accuracy for lower values of illuminance (values that are lower than the illuminance set-point defined for the space in question, after-which the users become troubled with the sunlight) is more valuable than a model that has average accuracy for the range of illuminance the sensor has.

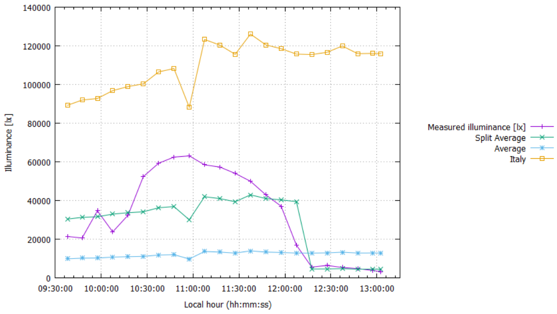


Figure 8: Comparison of the results obtained using different ratios.

Overall, using a ratio does not provide great results. For one, the radiation measured is on an horizontal plane, while the radiation that enters the room is through a window, which is on a vertical plane. This means that once the sun passes the vertical plane of the window, the radiation that enters the room is diffuse, which in turn decreases the illuminance measured, while on the horizontal plane there will not be a significant change in radiation measured. As such, using a ratio with the horizontal measurements will only result in an estimate of the illuminance measured, with considerable errors, and in order to obtain good results it is recommended to use a split value for direct and diffuse radiation to convert it to illuminance, in order to have the same behavior, otherwise, there will be an over or under-estimate of values measured.

4.2. Natural lighting

It is important to note that due to the location and orientation of the room, the peak of illuminance will be measured during the morning, and after noon, it will be mostly diffuse radiation that will light the room. Also, due to the position of the room, the nearby trees will influence the recorded illuminance, as it will not be possible to have the sun light all the room,, that is, it is not possible for the room to be completely illuminated from direct sunlight.

The distribution of the illuminance inside the room is represented in Fig. 9, and the data was measured in the 5th of April. In the figure it is represented the illuminance measured for P_1 (near the window) and P_5 (near the wall). It can be seen that for the early morning the value measured near the wall is higher than the value measured near the window. This can be explained as the vegetation near the room (tall trees) can influence how the direct sunlight hits the room, that is, due to the fact that the trees are about the same height as the window of the room, the tree itself blocks the sunlight near the window, but not towards the wall, giving the value near the wall higher. As the sun continues to rise, the impact of the vegetation is decreasing continuously, until the point it no longer influences the distribution of illuminance. After that point, the illuminance measured near the window is higher, and continues to rise, up until around noon, which is the point the sun hits the window with an angle of near 90°. On the opposite side, the value near the wall is lower, and starts to decrease, as it no longer is hit by direct sunlight, and because the angle of incidence starts to be more and more perpendicular, the amount of direct sunlight that enters the room is lower. After noon, all the light that enters the room is diffuse light – after which point it is possible to see a sharp decrease in the illuminance measured near the window –, and as such the illuminance measured is decreasing slowly.

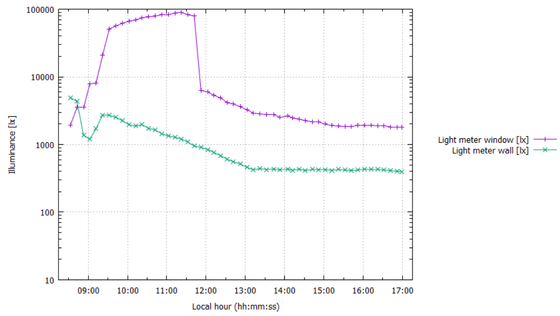


Figure 9: Distribution of illuminance inside the room provided by natural lighting.

4.3. Artificial lighting

To measure the impact the artificial lighting has in the illuminance distribution, it was measured in the five points of interest how the lights being turned on or off influence the measurement. To do so, the blinds were closed totally, and then it was measured the illuminance in the five points. As there are 4 rows of 4 lamps each, it will be named L_1 to L_4 the lamps in the same row the points of interest, being lamp L_1 the lamp near the window, and lamp L_4 the lamp near the wall.

The values measured are represented in Fig. 10. From the figure, it can be seen that turning L_4 on, the values near points P_5 and P_4 are higher than the rest. Turning L_2 on raises the value of point of interest P_3, as the lamp is located exactly on top of the point. The lamp also affects the other points of interest, as the values measured are higher than the values measured with only L_4 on. Turning L_3 on in conjunction with the L_4 and L_3 on rises considerably the values measured in P_4 and P_5, while rising slightly the illuminance measured in points P_3, P_2 and P_1. Finally, having all lamps turned on, it can be seen that the value for the points of interest P_4, P_3, P_2 and P_1 are approximately constant and equal, while the value measured for point P_5 is lower. This can be explained as the point P_5 does not have a lamp exactly on top of it, and the lamp has an object in the way to block direct lighting to the point of interest, resulting in a lower than expected measurement.

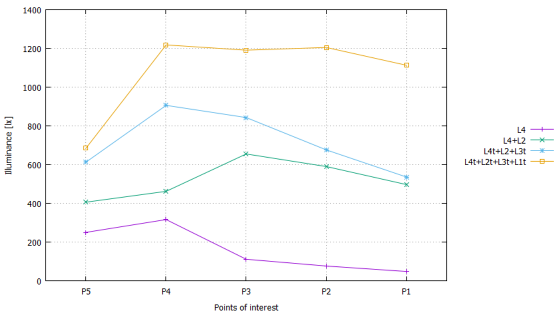


Figure 10: Distribution of illuminance provided by lamps.

Due to the orientation of the room, the values measured near the wall will always be lower than the values measured near the window provided there is not an obstacle to impact the illuminance. Due to this fact, it makes sense to turn on lamp L_4 first rather than for example lamp L_1, as the illuminance measured in the wall is lower. As such, a simplification can be made: if turning the lamp farthest away from the window does not provided satisfactory illuminance to the entire room, then it is required to turn the second farthest away lamp, and so forth. Doing so allows for a faster and smarter optimization as well as using only the necessary lamps to ensure comfortable working environment. Following this simplification, then several setups of lamps turned on and off can be rejected, and only a few configurations are useful to be used, which are the ones displayed in Fig. 10.

4.4. Prediction of the illuminance

For the prediction of illuminance, the program designed will ask for the illuminance measured from the Adafruit sensors or use the radiation from the weather station, though for the latter it may have high errors. It is important to note that for the first step, it converts the illuminance measured from the sensors to the values it would be measured from the light meter, and the values are more precise for lower end of the values read. This is relevant as for very high values the precision does not matter much, because the users will be uncomfortable the same; but for lower values (values below 1,500 lux, for example), the precision is important because it will be the difference if the blinds stay open and disturb the users due to direct sunlight, or if the blinds close and the users remain in a comfortable range of illuminance values. A schematic of the final algorithm used is in Fig. 11, which will be explained.

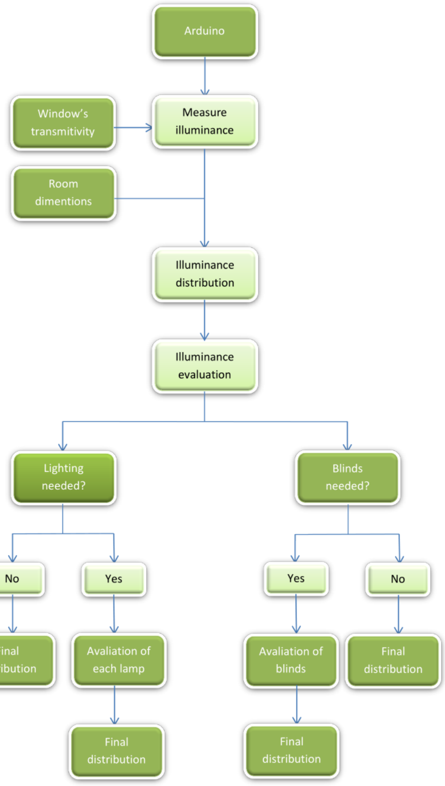


Figure 11: Representation of the algorithm used.

In Fig. 12 is displayed a first measurement and it's prediction. As it can be seen, the value measured and predicted for point of interest P_1 is very high (higher than the threshold defined as 1,500 lux). As such, it is necessary to use the blinds to reduce the illuminance. The program predicted that using blinds at 82% would guarantee that the illuminance measured would be lower than the threshold, and it is possible to see that the value is indeed below. The prediction and measurement are close in value (the error is slightly more than 26%), measured for the point of interest P_3.

On the other hand, when the value does not reach a certain threshold which was previously defined (when the point of interest P_5 does not reach 150 lux), then the electrical lighting turns on in order to raise the values. The prediction and correction

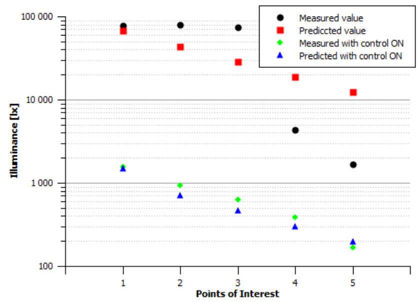


Figure 12: Prediction of illuminance and it's correction using blinds at 82%.

using the electrical lighting is shown in Fig. 13. Initially, the values recorded near the wall are lower than recommended: P_3, P_4 and P_5 are below than 150 lux. This type of conditions is uncomfortable for users because the it is too dark and as such, electrical lighting is required. Using only lamp L4 guarantees that the values are above the threshold. From the figure it can be seen that all points were raised, and in particular both predicted and measured values for P_1, P_2 and P_3 are extremely closed, showing the good prediction of the program. For points P_4 and P_5 the values are overestimated, but well above the threshold defined.

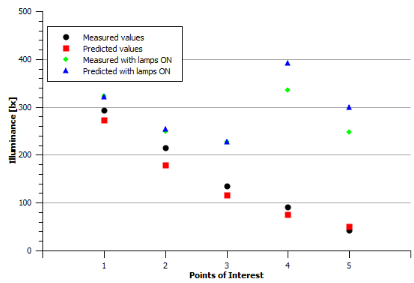


Figure 13: Prediction of illuminance and it's correction using lamp L4.

The table 2 provides a summary of the values measured throughout the day, and alongside the control method used to have the illuminance in the previously defined range of acceptable values. The time of the measurements were made in the local time, in early May, and were made over the points of interest. The values measured and predicted are side by side, and after applying a control method (either blinds or electrical lighting), the values are again displayed, now lower/higher depending of the control method.

For the morning, it is expected that the prevailing control method to be the blinds, as the room is facing East, and the peak of illuminance is measured in the morning. The electrical lighting will only be necessary if the sunlight can not provide sufficient illuminance to the users, and if the season considered is Summer, when the days are longer, then only at late afternoon/night will be necessary that type of control. As the day progresses, and with diffuse sunlight to light the room, the blinds will have a considerable weight in reducing the illuminance. Due to the fact that diffuse daylight lights the room not by direct incidence but through multiple reflections inside the room, changing the position of the blinds will greatly influence how the reflections occur. As such, the program will predict a higher than necessary percentage of closed blinds to have the illuminance in the acceptable range, meaning the illuminance measured will be lower than expected.

			Illuminance [lx]	
Local time	Point of interest	Control method	Measured	Predicted
9h30	P_1	Blinds at 83%	1567	1386
	P_2		1088	804
	P_3		693	527
	P_4		445	344
	P_5		191	225
11h00	P_1	Blinds at 82%	1673	1392
	P_2		1068	654
	P_3		697	428
	P_4		468	280
	P_5		212	183
13h20	P_1	Blinds at 80% with lamp L4 ON	1377	1269
	P_2		545	264
	P_3		429	226
	P_4		352	388
	P_5		304	314
16h10	P_1	Blinds at 78% with lamps L4+L2 ON	1724	1824
	P_2		445	622
	P_3		710	676
	P_4		580	475
	P_5		449	415

Table 2: Summary table for the values measured.

From the data provided by the table, it can be concluded that for the morning and for clear skies, it is necessary to use the blinds to lower the illuminance and bring it to comfortable range, as the high levels of illuminance can cause glare to the users in the room. It is suggested the use of blinds throughout the morning in order to control the amount of direct sunlight that enters the room and therefore the illuminance measured. After the moment where direct sunlight does not hit the window, the illuminance measured decreases and the blinds have an extra weight in the control of the room's illuminance. That can be observed for the measurements made after noon, as the suggested position of the blinds bring the illuminance to extremely low values. For these cases, the prediction of the position of the blinds does not yield good results; in fact, it would be recommended not using the blinds or using a lower percentage, in order to reduce the overall illuminance without compromising the values the users desire.

5. Conclusions

This work proposed to develop an autonomous system capable to measure and determine the illuminance in a classroom, and from those values decide if the use of blinds or electrical lighting to ensure the users worked in a comfortable range of illuminance. To do so several methods to predict illuminance were studied and analyzed. After this, a method was designed for this classroom. The final model was tested and validated in a classroom in Instituto Superior Técnico, a classroom which had controllable blinds and electrical lighting.

It was concluded through measurements that the program could predict the distribution with an admissible error, and it's suggestions to control the illuminance to the range of values recommended is successful as well. It was given an emphasis in the conversion to lower values of illuminance as for high values, it does not matter the precision as it will be uncomfortable for the users. The program was designed in Python, with which is possible to use in future work to automate the optimization.

This work managed to predict and optimize the distribution of daylight throughout a room and maintain a level of illuminance adequate for a good working environment using electrical lighting and blinds. In the lack of a sensor, this work proposes a simple approach to provide an estimate of illuminance taking into account the solar radiation measured in the exterior of the room.

5.1. Future work

Despite the prediction and management of the space is acceptable, more improvements can be made. For one, a more detailed study of the room can be made taking into account the light that can come in through the window from the corridor. A second improvement one can make is to try to predict the radiation the room will receive with more precision, avoiding that way the use of a sensor.

An important improvement that can be made is combining the program designed with an Arduino and a Raspberry Pi. The program was designed to take this into consideration, as with a Raspberry Pi it can be run in the room hidden from the users and used to determine the distribution. Coupling this with an Arduino allows for the Raspberry Pi to control both the blinds and/or the electrical lighting to ensure the illuminance stays in the range defined previously and the users are comfortable. The time for the measurements and the optimization made can be defined on the Raspberry Pi, deciding at which time of the program runs. It is suggested that running every 15 minutes provides a good estimate of the values and does not disturb frequently the users in case it is needed to control the blinds and/or the electrical lighting.

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