An approach for saving energy in smart environments

A.Fernandez-Montes [1], J. A. Ortega[1], L. Gonzalez-Abril[2], M.L. Vilchez[3], Luis M. Soria[1]

[1]Department of Computer Science, University of Sevilla, Sevilla, Spain
{afdez,jortega}@us.es
[2]Department of Applied Economics, University of Sevilla, Sevilla, Spain
luisgon@us.es
[3]Department of Applied Economics, University of Huelva, Huelva, Spain
lobato@uhu.es

Abstract

This article is focused on adapting lighting conditions to user lighting preferences. A theoretical analysis of lighting conditions is carried out and a case study is shown by means of the setup of the experimental environment and the empirical analysis of lighting conditions. Finally, a methodology for saving energy which adjusts luminance to user preferences is presented and a study on the consumption results is given.

1 Introduction

Saving energy in smart environment systems is one of the main goals of smart environment research. Wireless Sensor Networks (WSNs) -large networks of embedded devices, containing microcomputers, radios, and sensors- open new method approaches to saving energy. WSNs are used to retrieve data on lighting conditions.

2 Theoretical analysis

In order to study how artificial lighting alters lighting conditions in an indoor environment, a mathematical analysis is carried out which relates the luminance of a room with the lights alternatively switched off and on. A function $y = f(x)$ is considered where x and y denote the quantity of light, measured by the same device, with artificial lights first switched off and then on (both in the same unit). Clearly, the illumination with the lights on is equal to or greater than that with the lights off, and therefore, the inequality $0 \leq x \leq y$ holds.

Let us denote by x_{max}, the maximum quantity of light that the device can measure. This value is finite and it does not depend on whether lights are on or off and, hence, $x_{max} = f(x_{max})$.

The function $f(x)$ is an increasing function, and hence its first derivative is non-negative. The reason for this result is due to theoretical properties of light and that the artificial light has constant power such that for any $0 \leq x_1 < x_2 \leq x_{max}$ then $f(0) \leq f(x_1) \leq f(x_2) \leq f(x_{max})$. Hence, $0 \leq x \leq x_{max}$ and $0 \leq y_{min} \leq y \leq x_{max}$ where $y_{min} = f(0)$. Note that y_{min} denotes the minimum quantity of light with the lights on and it is reached when, in an indoor environment, only artificial light contributes to the lighting measurements.

With respect to the second derivative of $f(x)$, this must be non-positive since if it were positive then the first derivative of $f(x)$ would be an increasing function, which is impossible since the artificial light has constant power.

On the other hand, let us denote by μ the lighting threshold of an inhabitant, which means that μ is the minimum quantity of light that a user considers to be sufficient to render additional lighting unnecessary. This value depends on the preference of each user and can vary greatly depending on various factors, such as eye colour, ocular difficulty, different habits, and different use of the space. Nevertheless, an interval $I = [\mu - \alpha, \mu + \alpha]$ is considered in this article due to the uncertainty of the human perception of lighting conditions. Therefore, the most important value is $\mu + \alpha$ which must be estimated for each user and this value permits us to ensure that the user has sufficient light.

The luminance of the artificial light must be such that $y_{min} \geq \mu + \alpha$ since it must guarantee that the lighting preferences of the user can always be satisfied. Clearly, the artificial light must attain at least the value $\mu + \alpha$ since otherwise, the artificial light would have to be changed. This characteristic should be borne in mind when carrying out maintenance of a lighting system. It should be noted that the value y_{min} solely depends on the power of artificial light.

In Figure 1, an example of function $f(x)$ can be seen which verifies all theoretical conditions given.

It is worth noting that the lighting preferences of the user are exceeded in the zone denoted by I and II in Figure 1. Thus, a regulator of light can be installed (zone I) and a motion sensor can then be configured to switch off the light when it is turned on while no people can be detected indoors (zone II). Therefore, electricity consumption can be reduced with these two devices. Nevertheless, some empirical problems must be solved in order to achieve these energy savings.

3 Empirical analysis

An analysis of the lighting data retrieved in the environment above is carried out. The main objective in this experiment is to study lighting conditions when lights are switched on and when lights are off. The data is obtained from an indoor mote via the S1087 photodiode (that is, the PAR is used).

Tests, which include switching on and off lights at different moments of the day and night and pairing the luminance measures, are carried out 50 times. Let x and y be the retrieved

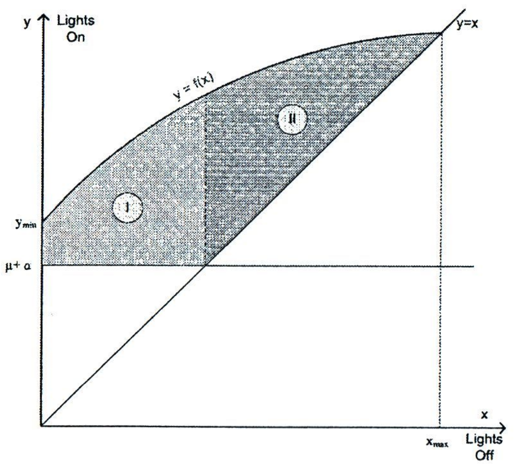

Figure 1: The relationship between lights off and lights on.

data of the luminance when lights are off and on, respectively (see Section 2).

In order to achieve a function which relates the x and y data, the linear correlation coefficient r is calculated. Since $r = 0.9827$ is near to 1, a linear model is obtained by using the least-squares methods (see Figure 2): $y = f(x) = 1.1039x + 97.15$. It is worth noting that this function is increasing and that $y_{min} = 97.15$.

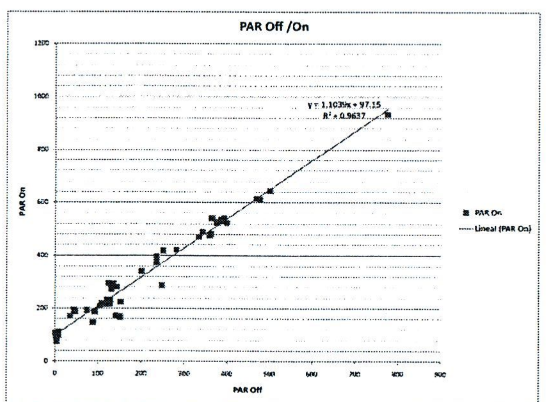

Figure 2: PAR Off / PAR On Relation

The linear regression of x with respect to y is $x = f^*(y) = 0.873y - 77.15$. That is, if y is denoted PAR_{on} and it is known then an estimated value of x, denoted by $PAR_{off-Estimated}$, can be obtained.

4 Saving Energy

Under the conditions stated above, it can be guaranteed that μ+a is the quantity of light that a inhabitant considers. Therefore, in order to save energy, indoor artificial lights can be adjusted to this $\mu + \alpha$ value.

The main goal of the current work is to use the knowledge learned to save energy. Data from *motes* have been retrieved over several months in different periods of the year and data has been stored in a relational database. The methodology proposed used only one part of the dataset. This subset is shown in the list below:

- **Indoor lighting PAR.** This variable represents the quantity of light received from the indoor Sentilla *Tmote* S1087 photodiode. It is a continuous variable which ranges from 0 lux upwards.
- **Indoor light state.** This variable represents the state of the lights of the room received from the X10 appliance module. It is a discrete variable, with value 0 for lights off, and 1 for lights on.
- **Motion.** This variable represents the detection of motion sent by the MS13A X10 device. It is a discrete variable, with value 0 for no motion, and 1 for motion detected.

From this dataset, several statistical analyses of lighting usage are made. For example, how long lights are left on and off, or when the quantity of light (PAR) is greater or less than user preference (μ_{PAR}). This analysis is shown in Table 1.

As can be observed in Table 1, the lights are on for 18.84% of the total time, that is, about 4.8 hours a day, or 33.6 hours a week (no-working days are also included). The most important value to focus on is the number of instances that the lights are on while PAR values are greater than μ_{PAR}, since this means that the lighting conditions exceed those necessary to satisfy the preferences of an inhabitant and hence energy is being wasted. Abnormal behavior of the illuminance sensor is present in the table since 0.15% of the instances have a value less than μ_{PAR} when the lights are on. These instances should be considered as error values, although the percentage is negligible. These values are computed for the μ_{PAR} of the 'AFM' inhabitant

The next task is to compute the quantity of luxes in all the instances of the database where the lights are on (PAR_{On}):

$$\sum_{lights=On} (PAR_{On} - PAR_{OffEstimated})$$

where $PAR_{OffEstimated}$ is the estimated PAR value by regression $f^*(PAR_{On})$ with the lights off (see Subsection 3).

The wasted luxes can now be calculated (see Figure 1) as:

$$\sum_{lights=On} [PAR_{On} - max(\mu_{PAR}, PAR_{OffEstimated})]$$

Notice that the maximum between μ_{PAR} and $PAR_{OffEstimated}$ is subtracted from the illuminance detected by sensors. This is the border line between zones I and II shown in the theoretical analysis in Figure 1.

The energy consumed by the lights is calculated as follows:

totalTimeOn $*$ #tubes $*$ (wattsPerTube$/1000$) $=$ Total KWh

	Total		PAR			
			PAR>μ_{PAR}		PAR<μ_{PAR}	
	#instances	%	#instances	%	#instances	%
lights On	13810	18.84	**13710**	52.53	70	0.15
lights Off	59490	81.16	12390	47.47	47100	99.85
TOTAL	73300	100	26100	100	47170	100

Table 1: Study of lighting behavior.

	interval			per year		
Days computed	101.8			365		
Days with lights on	19.2			68.77		
Total Luxes generated	167,010,000			598,775,280		
Total Luxes wasted	119,715,110			429,210,527		
	KWh	CO_2 (kg)	euros	KWh	CO_2 (kg)	euros
Total Consumption	132.6	36.3	17.9	475.32	130.24	64.24
Total Waste	95.0	26.0	12.8	340.72	93.36	46.05

Table 2: Light consumption and wasting per interval and year.

and the undesired CO_2 generated is:

Total KWh $*$ 0.274 Kg/KWh $=$ total Kg of CO_2

By supposing a linear relation between generated luxes and their consumption, the total **waste of lighting** can be computed as about **72% of consumption**. Making a smart adjustment of the lights could save about 340KWh, 93 kg of CO_2 and 46 euros (0.14 euros per KWh) a year per standard office, based on the data retrieved for the case study and the methodology proposed.

It is worth noting that the adjustment of lights is not trivial, fluorescent lights are generally suitable for dimming, and hence a discretization of lights is carried out. A total of 16 fluorescent lights are employed so that some or all of them can be switched on at any time. Moreover, the regression line of the relation PAR On / Par Off can be used (instead of Par Off / Par On as shown in Subsection 3). In this way, the quantity of luxes ($PAR_{OffEstimated}$) when the lights are off can be estimated before any action is executed. See Table 2 for an analysis of the results.