Modeling of lighting behaviour of a hybrid lighting system in inner spaces of Building of Electrical Engineering

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Abstract. This paper presents the modelling of lighting behaviour of a hybrid lighting system - HLS in inner spaces for tropical climate. HLS aims to mitigate the problem of high electricity consumption used by artificial lighting in buildings. These systems integrate intelligently the daylight and artificial light through control strategies. However, selection of these strategies usually depends on expertise of designer and of available budget. In order to improve the selection process of the control strategies, this paper analyses the Electrical Engineering Building (EEB) case, initially modelling of lighting behaviour is established for the HLS of a classroom and an office. This allows estimating the illuminance level of the mixed lighting in the space, and energy consumption by artificial light according to different lighting control techniques, a control strategy based on occupancy and a combination of them. The model considers the concept of Daylight Factor (DF) for the estimating of daylight illuminance on the work plane for tropical climatic conditions. The validation of the model was carried out by comparing the measured and model-estimated indoor illuminances.

1. Introduction
The artificial lighting in buildings is a significantly energy load [1]. The HLS can reduce this consumption, since these are based on control techniques taking advantage of the daylight reducing the use of artificial lighting [2]. Studies have demonstrated the benefits of the HLS; [3] shows an energy saving of 30% in Torino (Italy) by using fluorescent lamps and [4] presents a HLS used in Shanghai (China), which is analyzed for fluorescent and LED lamps, where energy consumption is reduced approximately 41% and 66%, respectively. Because of the potentiality of the HLS in the buildings, it is necessary continue with the conducting studies to intensify the obtaining of benefits. Such is the case of modeling of lighting behavior in inner spaces for the design, control and optimization of HLS.

In that sense, this paper addresses the modeling of lighting behavior and energy consumption of two study cases of current HLS in Electrical Engineering Building (± 7.1 ° latitude) of the Industrial University of Santander (Bucaramanga, Colombia).

This work was conducted in seven stages. First stage is a brief review of the literature (Section 2); second stage consists of the fundamentals of modeling obtained (Section 3); third step is the description of the study cases (Section 4); fourth stage addresses the measurement process in the selected spaces (Section 5); fifth and sixth stages present the formulation of models of lighting behavior and energy consumption, respectively (Sections 6 y 7); finally, seventh stage shows the results of the validation of the models of the lighting behaviour.
2. Literature review

The lighting behavior can be described from models representing the conditions of a space and the relationship with several parameters and variables. For example, Daylight Factor (DF) is a relationship between the interior daylight and external daylight. This factor has been modeled of different ways, including a matrix as a function of the geometric position in the space [5], [6]. Likewise, Parise et al. [5] model the interior daylight as a function of the geometric position and DF in the room. Moreover, the total interior illuminance is modeled as the combining of the artificial light and daylight on the working plane [6], [7]. Similarly, Kamaruzzaman et al. [8] evaluated the performance of the lighting in an office building in the tropical zone from of the modeling of artificial lighting, daylighting, position of the sun, and kind of sky, among others factors.

Other factors related to indoor lighting are subject of modeling, as illuminance on the work surface, control, and energy consumption. Parise et al. [5] describe the control lighting strategies by a set of equations. Fischer et al. [9] present the relationship between the dimming levels of luminaries and the illuminance on the working plane. Moreover, Roisin et al. [10] show a linear relationship between the power consumption by lamp and its luminous flux. While, Osma et al. [11] and Ozenc et al. [12] determine polynomial functions relating the power consumption to the dimming level and the energy consumed according to dimming levels. Depending on the purpose of the modeling, it can be mathematical or analytic type, based on computational tools as Matlab [6]. Also, it can be developed from statistical methods (linear regression [10], multivariate non-linear regression [13]), artificial intelligence techniques (machine learning [9], neural network [14], fuzzy logic [7]), and through lighting simulation tools (Radiance [9], Dialux, [10], Virtual Environment (VE) [8], Daysim [10]).

3. Fundamentals of modeling

The total illuminance (ET) (lux) on an interior point of the working plane for a room is the sum of all contributions of interior daylight (ED) (lux) and artificial illuminance (EA) (lux), being the last one provides by luminaires, which may be or not managed by a lighting control strategy [6]. Therefore, the total illuminance on an interior point can be defined as:

\[
ET(t, x, y) = EA(t, x, y) + ED(t, x, y)
\]

Where the artificial illuminance \(EA(t, x, y)\) is a function of distance existing between horizontal projection of mid-point of luminaire until mesh point (measurement point of the illuminance). IT's value depends on daylight availability. Such adjustment is performed by a lighting control strategy. \(ED(t, x, y)\) is a function of geometric position and varies as a function of the time [5]. It is calculated by equation (2) for each point \((x, y)\) of the space. Where \(E_E(t)\) (lux) is the external daylight illuminance and \(DF(%)_{(i,j)av}\) is the daylight factor average for each point \((x, y)\) of room.

\[
ED(i,j)(t) = E_E(t) \cdot DF(%)_{(i,j)av}
\]

The \(DF(%)_{(i,j)av}\) estimation considers these aspects: i) In tropical places as Bucaramanga, DF must to be obtained with respect to incident daylight at the façade and not at the roof, since vertical external daylight can provide more accurate information than the horizontal case. Furthermore, in a lit side room, daylight may be more nearly proportional to the amount of daylight falling on the window, rather than to the external horizontal daylight [8]; ii) DF must be calculated by source, so must not be combined side sources (windows of different facades) nor zenithal sources (solar tubes).

4. Description of the study cases

This paper presents two study cases of HLS applied in the Electrical Engineering Building (EEB) of Industrial University of Santander. The first study case is a classroom located in the third floor (see Figure 1), which has a HLS consisting of an lighting control by on/off switching of lamps in response to occupancy and daylight availability (one occupancy sensor including an on/off photocell OSC10-
M0W), twelve fluorescent luminaires (4x14W T5 – electronic ballast), and windows at the south façade. The second case is a meeting room located in the fifth floor (see figure 2); its HLS is composed of a lighting control by dimming (10 % - 100%) of the lamps in response to occupancy and daylight availability (one occupancy sensor OSC10-M0W and dimming photocell LS-301), four fluorescent luminaires (4x14W T5 – dimming ballast), and windows at the south façade.

5. Measurement process
The matrix models are based on measurements of daylighting and artificial lighting, which were taken with light meters according to a mesh for a height of 0.75m (working plane). The measurement mesh consists of a point set established in accordance to the dimensions of space.

The figure 3 and figure 4 show the mesh of measurement of selected spaces, with 18 points (3x6) and 9 points (3x3), respectively. The artificial illuminance was measured at night, whilst during daytime were taken the measurements of interior daylight illuminance and exterior daylight illuminance ($E_{E1}, E_{E2}$) for calculating to DF. Each point of mesh is an array element ($e_{i,j}$).

6. Model of lighting behavior
6.1. Estimation of Daylight Factor (DF)
DF is the percentage ratio of interior daylight illuminance to external daylight illuminance [8]. In this paper, DF was calculated as an average value in each point $DF(\%)(i,j)_{av}$. The matrix model of DF for two spaces is shown by the equation (3), where $E_{D(i,j)}(t)$ and $E_{E(i,j)}(t)$ are the interior daylight illuminance (in the absence of artificial light) and the external daylight illuminance, respectively; which are measured for every hour of sunshine in each measurement points and n is the number of hours considered for calculating of $DF(\%)(i,j)_{av}$.

$$DF(\%)(i,j)_{av} = \left( \frac{\sum_{t=1}^{n} \frac{E_{D(i,j)}(t)}{E_{E(i,j)}(t)}}{n} \right) \cdot 100$$ (3)
Results indicate that DF tends to be the same during daytime and varies according to geometric position inside the room, as shown in figure 5 and figure 6. The highest values of DF are presented close to the window and decreases as they move away from this.

![Figure 5. Distribution of DF(%) in the class room](image1)

![Figure 6. Distribution of DF(%) in the meeting room](image2)

6.2. Daylight illuminance

The interior daylight illuminance $E_{D(i,j)}(t)$ (lux) in each point is estimated for every time instant by means of the matrix model of illuminance given by equation (4).

$$E_{D(i,j)}(t) = E_{E(i,j)}(t) \cdot DF(\%)(i,j)_{av}$$  \tag{4}

6.3. Artificial illuminance

The interior artificial illuminance is measured in lux for each point of classroom $E_{A,CR(i,j)}$ (lux) and of the meeting room $E_{A,MR(i,j)}$ (lux). The artificial illuminance matrices are presented below.

$$E_{A,CR(i,j)} = \begin{bmatrix} 422 & 440 & 448 & 468 & 461 & 422 \\ 500 & 542 & 536 & 528 & 533 & 482 \\ 659 & 697 & 680 & 702 & 717 & 618 \end{bmatrix}$$

$$E_{A,MR(i,j)} = \begin{bmatrix} 322 & 461 & 301 \\ 588 & 821 & 535 \\ 553 & 763 & 530 \end{bmatrix}$$

6.4. Total interior illuminance - $E_T(i,j)(t)$

The equation (5) allows the calculation of $E_T(i,j)(t)$ (lux) for every time $t$ and every point of the mesh; where $E_{A,CS(i,j)}(t)$ is the artificial illuminance defined by the lighting control strategy of each space.

$$E_T(i,j)(t) = E_{D(i,j)}(t) + E_{A,CS(i,j)}(t)$$  \tag{5}

6.5. Artificial illuminance according to control strategy

The values of $E_{A,CS(i,j)}(t)$ depends on adjustment done by lighting control strategy. This adjustment is a function of factors such as: state of switching of luminaires, availability of daylight, occupancy, minimal value of daylight and strategy of lighting control. $E_{A,CS(i,j)}(t)$ for the classroom varies between zero and the values of artificial lighting matrix according to following conditions:

$$E_{A,CS(i,j)}(t) = \begin{cases} 0 & \text{if } Oc_t = 0; \\
0c_t = 1 \land Oc_{t-1} = 0 \land e_{nat,pc}(t) > e_{min}, \\
0c_t = 1 \land Oc_{t-1} = 1 \land lum_{t-1} = "Off" \land e_{nat,pc}(t) > e_{min} \\
0c_t = 1 \land Oc_{t-1} = 1 \land lum_{t-1} = "On" \\
0c_t = 1 \land Oc_{t-1} = 1 \land lum_{t-1} = "Off" \land e_{nat,pc}(t) < e_{min} \end{cases}$$  \tag{6}

$$E_{A,CS(i,j)}(t) = E_{A(i,j)} \begin{cases} Oc_t = 1 \land Oc_{t-1} = 1 \land lum_{t-1} = "On" \\
Oc_t = 1 \land Oc_{t-1} = 1 \land lum_{t-1} = "Off" \land e_{nat,pc}(t) < e_{min} \end{cases}$$  \tag{7}

Where $Oc_t$ and $Oc_{t-1}$ are the current state and previous state of the occupancy, respectively; $e_{nat,pc}(t)$ is the minimal value of daylight illuminance in the space; $e_{min} = 400$ lux is the minimal value of illuminance that must be ensured according to the RETILAP [15]; $lum_{t-1}$ is the On/Off state of
luminaires for $t-1$. The artificial illuminance of the meeting room $E_{A,CS(i,j)}(t)$ is defined by the required artificial illuminance $E_{A,req(i,j)}(t)$ (lux) to achieve a value of $e_{min}$ equal to 435 lux. $E_{A,req(i,j)}(t)$ is calculated from the following conditions:

$$E_{A,req(i,j)}(t) = e_{min} - \min(e_{D21}:e_{D23}) \{ Oc = 1 \land \min(e_{D21}:e_{D23}) < e_{min} \}$$

$$E_{A,req(i,j)}(t) = 0 \{ Oc = 0; \}

$$E_{A,req(i,j)}(t) = \min(E_{A,i,j}) \{ Oc = 1 \land \min(e_{D21}:e_{D23}) = 0 \}$$

Where $\min(e_{D21}:e_{D23})$ is the minimum value of daylight that can be given on the working plane (table of meeting). The second component is the relationship between artificial illuminance according to control in percentage and the dimming voltage (0 - 10 V), which is represented by the equation (11).

$$E_{A,CS} = -0.0024DV^3 + 0.031DV^2 + 0.022DV + 0.0606. \quad (11)$$

Considering $E_{A,req(i,j)}(t)$ and the equation (11), it can be determined the dimming voltage DV, from which the matrix $E_{A,CS(i,j)}(t)$ of meeting room can be estimated by equations (12) and (13).

$$E_{A,CS(i,j)}(t) = 0 \{ E_{A,req(i,j)}(t) = 0; \}

$$E_{A,CS(i,j)}(t) = (−0.0024DV^3 + 0.031DV^2 + 0.022DV + 0.0606) \cdot E_{A(i,j)} \{ e_{A,req23} / e_{A23} > 0.01 \}$$

7. Modeling of energy consumption

7.1. Class room
The energy consumption of lighting system is determined by the equation (14). Where $P_{lu,t}$ is the power of the luminaries (80W), $n_{lu}$ is the number of luminaires (12), $h_T$ is the total hours of operation of the luminaires, $P_{OS}$ is the occupancy sensor power (1 W) and $n_{OS}$ is the number of occupancy sensors (2). In general, the operating daily time is 10 hours, although the artificial lighting is on only 6 hours because the control strategy uses the daylighting; thus the daily energy consumption is near to 5.8 kWh.

$$E_{CT} = P_{lu,t} \cdot n_{lu} \cdot h_T + P_{OS} \cdot n_{OS} \cdot 24hr \quad (14)$$

7.2. Meeting room
The meeting room has 4 dimming luminaries of 78W. The power consumption of each luminary ($P_{lu}$) varies according to DV and is given by the equation (15). The total energy consumption of lighting system of the meeting room is given by the equation (16). Where $EC_{t,lu}$ is the total energy consumed by the luminaires, $EC_{t,OS}$ is the total energy consumed by occupancy sensor, and $EC_{t,fdim}$ is the total energy consumed by dimming photocell.

$$P_{lu} = -0.108DV^3 + 1.217DV^2 + 3.274DV + 31.403$$

$$E_{C,total} = EC_{t,lu} + EC_{t,OS} + EC_{t,fdim} \quad (15)$$

$$E_{C,total} = EC_{t,lu} + EC_{t,OS} + EC_{t,fdim} \quad (16)$$

The daily values of $EC_{t,OS}$ and $EC_{t,fdim}$ are always 24Wh, while the $EC_{t,lu}$ varies for every hour according to values of DV and availability daylighting. Considering a typical daily conditions work, as is described by Osma et al. [11] (previous work about these spaces), it is possible to estimate that energy consumption is around 0.6 kWh/day.
8. Validation
In order to validate the matrix model, a comparison between the measured and the estimated total interior illuminances $ET_{ij}(t)$ was done for of the meeting room at 3:22 p.m. (to see Figure 7). Furthermore, was calculated the normalized mean squared error (NRMSE) and mean absolute error (MAE), whose values was 6.9% and 15.96 lux, respectively. Based on the presented comparison between the measured and the estimated total interior illuminances and the error measures (MAE and RMSE), the validation of the model can be considered as successful.

![Figure 7](image_url)

**Figure 7** Comparing the measured and model-estimated total interior illuminance at 3:22 p.m.

9. Conclusions
The study has shown that the presented model of total interior illuminance $ET_{ij}(t)$ can be used as a satisfactory method for estimating the illuminance in inner spaces.

The proposed models of lighting behavior and energy consumption are simple mathematical equations that can be useful for the study of HLS. For example, in the development of tools allowing to select of optimal way the components (sensors, photocells) of control strategy of the HLS, according to criteria such as minimal financial cost and minimal energy consumption, among others.

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