Smart Controls for Lighting Design: Towards a Study of the Boundary Conditions

I. Acosta, M. A. Campano, P. Bustamante, and J. F. Molina

***Abstract*—This research aims to determine the effect of the lighting smart controls in the energy consumption in buildings, according to the geometry of the room, the window size, the reflectance of the inner surfaces and the location of study. For this purpose, two lighting smart controls are proposed: one based in an On/Off lighting control with separated lines and other with a dimming control. The analysis of both control systems is carried out by using daylight dynamic metrics, such as the daylight autonomy and the continuous daylight autonomy. The results quantify the effect of the architectural variables of the room in the performance of the lighting smart controls.**

***Index Terms*—Smart controls, energy saving, window design, daylight autonomy, continuous daylight autonomy.**

I. Introduction

Nowadays, energy saving is one of the most important variables in building design. Proper use of daylighting is essential in reducing energy consumption in electric lighting while maximizing visual comfort for occupants. As can be seen from previous research, daylighting improves visual perception [i] and synchronization of the circadian stimulus [ii]. Accordingly, windows are the greatest resource to allow daylight into buildings [iii]. A suitable window design also improves the thermal comfort and produces a significant energy savings in electric lighting [iv], [v].

Daylight factor is the simplest and most common measure to quantify the daylight allowed by a window, as they express the potential illuminance inside a room in the worst possible scenario, under overcast sky conditions when there is less exterior daylight. Moreover, this definition is recognized by the CIE as one of the key metrics in lighting [vi]. Since daylight factors are assessed under overcast conditions, the sun's position is not relevant, so the calculation is independent of the location of the room. Therefore, the measurement of daylight factors does not depend on time, window orientation or location of the room.

However, the daylight factor is not a completely reliable metric when defining the energy savings in electric lighting, given that it ignores daylight produced under clear sky conditions [vii].

Therefore, as stated in current research, it is increasingly common to use dynamic metrics in daylighting studies, defining the energy savings according to the orientation of the window, location of the room and sky conditions. One of the most extended dynamic metrics is daylight autonomy, proposed in 1989 by the *Association Suisse des Electriciens* [viii] and redefined by Reinhart *et al.* [ix]. Daylight autonomy is defined as the percentage of the year when a minimum illuminance threshold is met by daylight alone. According to this definition, the higher the daylight autonomy, the lower the energy consumption in electric lighting.

Window design has been widely studied in the analysis of daylight factors. Most current treatises on lighting in architecture [x], [xi] study the proper sizes and shapes for windows. Studies on window design are usually based on empirical methods and lighting simulation programs. The results obtained from empirical methods are not accurate, as can be deduced from the daylight factor method [xii], which is defined as a calculation procedure with limited calculation variables. However, current lighting simulation programs provide a better accuracy than empirical procedures [xiii], [xiv], making them useful tools for the study of daylighting and energy savings in architecture.

At present, lighting smart controls are not really widespread, due to the initial costs, the difficulties in the execution and the limitations of the individual management. However, these strategies allow a noticeable reduction in energy consumption of up to 45% using dimmers and close to 30% by mean of occupant detectors [xv]-[xvi].

Lighting smart systems require the determination of different variables: window size, which clearly affects to the electricity consumption, as well as the reflectance of the inner surfaces of the venue [xvii]. The location of the space is also decisive [xviii]. The most common smart systems are based in the separated control of the luminaires and the dimmers which adjust the luminous flux of the lamps [xix], [xx].

The lighting control systems also have a noticeable effect on the thermal comfort of occupants, due to solar heat gain [xxi]. Therefore, it is important to highlight the benefits from all these lighting systems, quantifying the effect of architecture in their performance.

II. Objectives

This research aims to determine the effect of the lighting smart controls in the energy consumption in buildings, according to the geometry of the room, the window size, the reflectance of the inner surfaces and the location of study. For this purpose, two lighting smart controls are proposed: one based in an On/Off lighting control with separated lines and other with a dimming control. The analysis of both control

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systems is carried out by using daylight dynamic metrics, such as the daylight autonomy and the continuous daylight autonomy.

Accordingly, this research is based on two main objectives:

1). To represent the quantification of daylight autonomy and continuous daylight autonomy in more conventional calculation models, so that it serves to determine the energy consumption according to different lighting smart controls.

2). To conduct an analysis of the resulting daylight dynamic metrics and determine the effect of the architectural design in the performance of smart controls.

The conclusions of this research are summarized in three graphs which define the effect of the architectural variables for different smart controls.

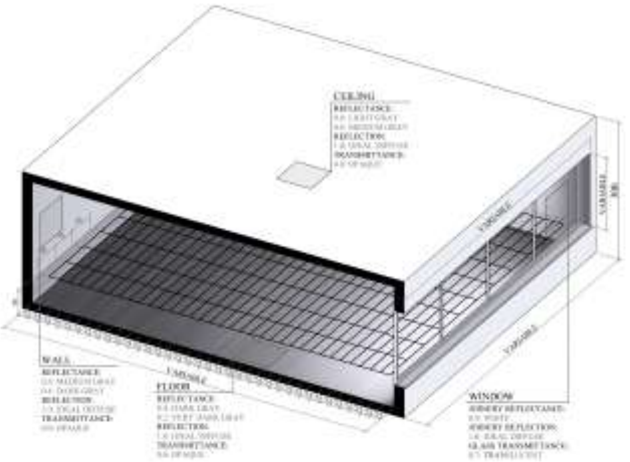

Fig. 1. Calculation model.

III. Methodology

A. Model

The calculation model for the analysis of daylight autonomy is defined as a room with 3.00 m high. The depth of the room is variable, in order to conclude its effect on the performance of smart controls. Three room depths are considered for this research: 3, 6 and 9 meters. The ceiling, walls and floor of the room have a thickness of 0.25 m.

A window of variable size is located in one fa çade. The double-leaf window has 0.05 m thick joinery and double glazing which produces a solar factor of 0.75. The reflectance of the inner surfaces of the calculation model is variable, accordingly two basic room models –with light or dark surfaces– are defined.

The inner surfaces of the room are diffuse reflectors and the Lambertian reflection of daylight is therefore directly proportional to the cosine of the angle between the observer's line of sight and the surface normal. All variables of the calculation model are shown in Figure 1:

The measurement of daylight autonomy is performed on the axis of symmetry of the calculation model. These variables have been established according to the most common parameters of shape, size and position of the window of a conventional office room.

Accordingly, the calculation model is defined by the following variables, abbreviated in a code name:

3, 6, 9: Depth of the room, measured in meters

30, 60, 90: Window to fa çade ratio, measured as a percentage of the fa çade surface..

B, D: Room reflectance values. B corresponds to bright surfaces, while D represents dark surfaces.

L, S, M: Room location, which can be London (L), Stockholm (S) or Madrid (M).

B. Program

The analysis of the daylight autonomy was carried out using simulation program DaySim 3.2, which calculates luminous distribution using the ray-tracing process. Several studies have confirmed the correct behavior of this calculation program [xxii], determining their accuracy by applying the CIE test cases [13]. The calculation parameters used in this program are shown in Table I:

TABLE I: Calculation Parameters of Daysim 3.2

Radiance Simulation Parameters	Ambient Bounces	7
	Ambient Divisions	1500
	Ambient Super-samples	100
	Ambient Resolution	300
	Ambient Accuracy	0.05
	Limit Reflection	10
	Specular Threshold	0.0000
	Specular Jitter	1.0000
	Limit Weight	0.0040
	Direct Jitter	0.0000
	Direct Sampling	0.2000
	Direct Relays	2
	Direct Pretest Density	512

C. Sky Conditions

The weather conditions correspond to the following locations:

- Stockholm (Sweden): 60 ºnorth latitude, mainly overcast skies.
- London (UK): 50 ºnorth latitude, predominantly overcast skies.
- Madrid (Spain): 40 ºnorth latitude, mainly clear skies.

The weather data is obtained from Energy Plus [xxiii], considering the Perez *et al*. sky model [xxiv].

D. Calculation Conditions

The calculation of daylight dynamic metrics have been developed considering an occupancy hours from 8:00 am to 5:00 pm, with one break to lunch. The illuminance threshold for the daylight autonomy calculation is 500 lux. The blind control is active, so the users avoid direct sunlight on work plane.

All the windows in this study are facing north, avoiding direct sunlight, since this is the worst case study for determining the interior illuminance values [xxv]. In addition, exterior solar obstructions are not considered for this research.

E. Calculation Metrics

Two dynamic metrics were under study in this work. The first of these is daylight autonomy (DA), a concept conceived by the Association Suisse des Electriciens [8] and redefined by Reinhart et al. [9]. This metric is defined as the percentage of the year when a minimum illuminance threshold is met by daylight alone so that the higher the daylight autonomy, the lower the energy consumption in electric lighting. This metric can be defined as equation (1):

$$DA=\frac{\sum_i wf_i\, t_i}{\sum_i t_i} \quad \in [0,1] \quad wf_i=\begin{cases} 1 \text{ if } E_D \geq E_L \\ 0 \text{ if } E_D < E_L \end{cases} \qquad (1)$$

where t_i is the occupied time in a year, wf_i is the weighting factor which depends on the illuminance threshold, E_D is the daylight illuminance measured at a given point, and E_L is the illuminance threshold.

The second dynamic metric is continuous daylight autonomy (DAC) which represents the percentage of the year when a minimum illuminance threshold is met by daylight alone, considering a partial credit linearly to values below the threshold defined [xxvi]. Therefore, this metric can be expressed as equation (2):

$$DAC=\frac{\sum_i wf_i\, t_i}{\sum_i t_i} \quad \in [0,1] \quad wf_i=\begin{cases} 1 \text{ if } E_D \geq E_L \\ E_D/E_L \text{ if } E_D < E_L \end{cases} \qquad (2)$$

According to the previous formulae, the dynamic metrics are calculated depending on the weather conditions which define daylight illuminance, the illuminance threshold and the occupancy time, using a typical year.

Following the definition of DA, the energy consumption in electric lighting can be determined, knowing the time throughout the year when the luminaires are switch on. As in the previous metric, the quantification of DAC serves to determine the energy consumption of a dimming system to control the luminous flux of the lamps.

F. Smart Control Strategies

The previous metrics, explained above, serve to determine the energy consumption in electric lighting of different smart controls strategies, such us dimmers or switch systems with separated lines. The smart controls proposed for this research are summarized below:

- On/Off lighting control with two different lines of luminaires, where one line serves for the façade lighting line and another is for back of the room.
- Dimming lighting control with two different lines, where one line serves for the façade lighting line and another is for the rest of luminaires located at the back of the room. The dimmer is controlled by an illuminance meter which detects the daylight illuminance, adjusting the power supply for the lamps.

IV. Results

Fig. 2 shows the measurement of daylight dynamic metrics in the calculation model with a window to façade ratio of 60%, 6 m depth and a high reflectance value of the inner surfaces. The location is Madrid. This section view serves as an example of the calculation models defined in this research.

The section view also shows the energy consumption per luminaire line, according to the smart control strategies exposed above.

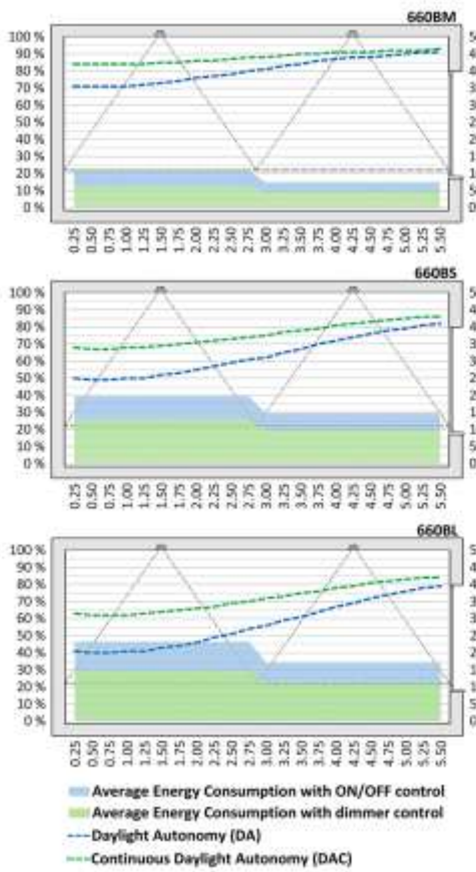

Fig. 2. Results of dynamic metrics and average energy consumption according to a room section of 6 m depth.

In accordance with the results observed for the dynamic metrics defined, the average energy consumption can be defined according to the proposed smart controls.

As can be deduced, the energy consumption is noticeable higher for the smart system with On/Off control, while the dimming control achieves an energy saving up to 45% with respect to the previous one. The benefits promoted by the dimming system is even higher for rooms with a low reflectance of the inner surfaces.

Moreover, there is a noticeable difference between the energy consumption produced in the first line of luminaires and those located in the back of the room. The luminaire line near the façade produces an energy saving close to 35% with respect to those located in the back in the case of an On/Off control. This difference is slightly lower in the case of a dimming system, where the divergence between both lines is near 25%. Therefore, it can be concluded that the dimming control allows a higher energy efficiency and minimize the energy consumption in the back of the room.

V. Analysis of Results

After performing the trials and determining the quantification of daylight autonomy, an analysis of results of the model calculation is carried out under the conditions established in the methodology, according to the different variables.

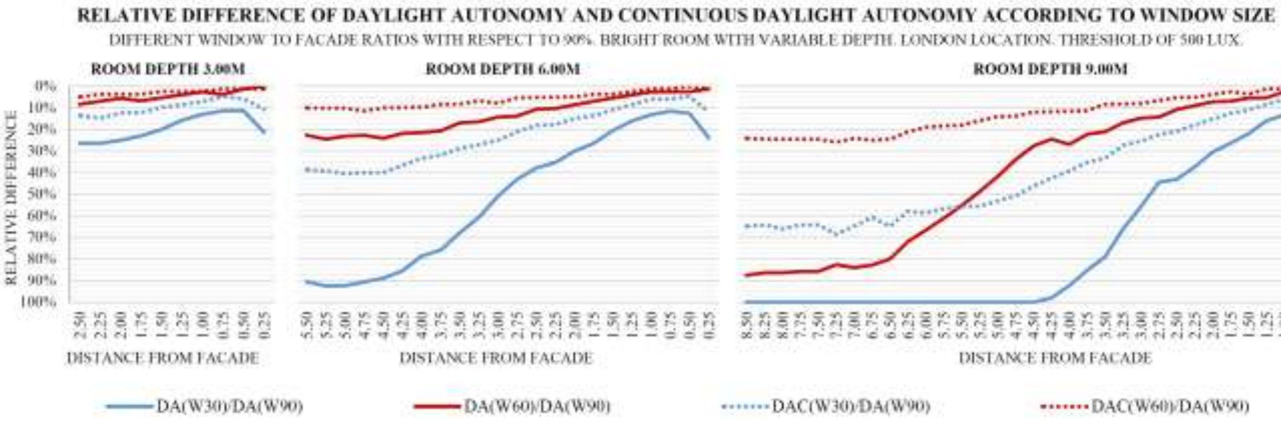

Fig. 3. Relative difference of daylight dynamic metrics according to window size.

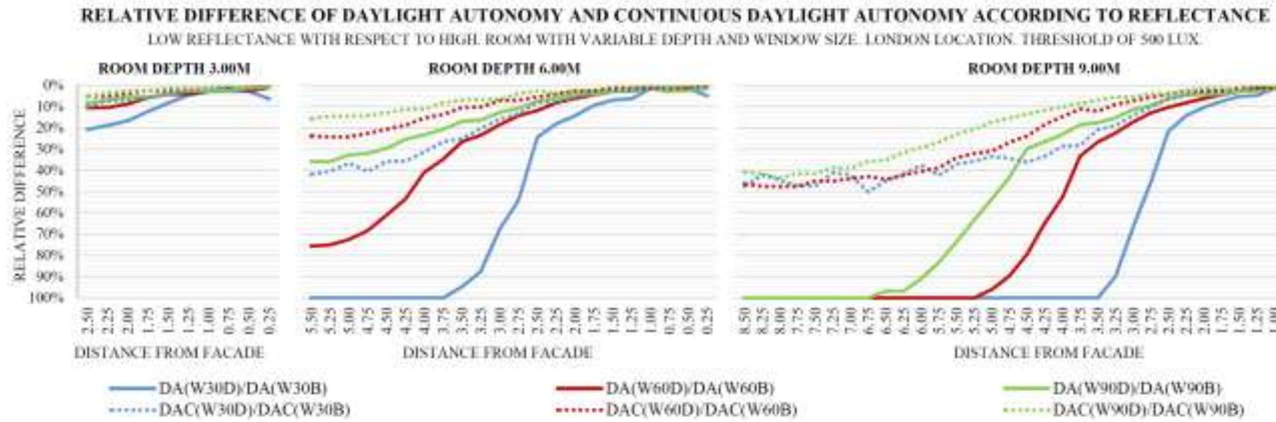

Fig. 4. Relative difference of daylight dynamic metrics according to room reflectance.

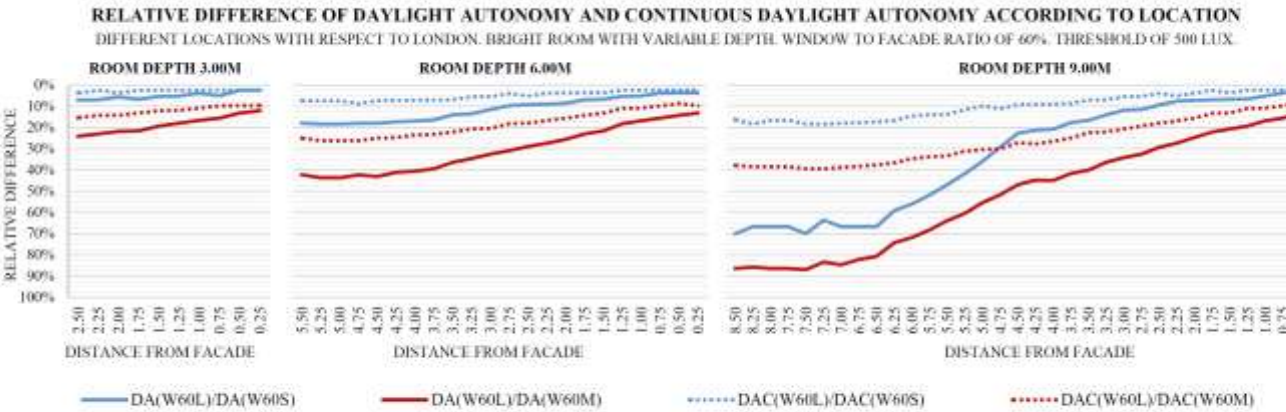

Fig. 5. Relative difference of daylight dynamic metrics according to room location.

A. Analysis of Window Size

The first trial corresponds to the variation of the window size, considering an invariable reflectance of the inner surfaces of the room and London location.

Figure 3 represents the relative difference of the analyzed dynamic metrics according to window size. Three room depths are shown in the graph. The daylight autonomy comparison is shown in a solid line, while the continuous daylight autonomy is represented in a dash line.

The analysis is carried out comparing the small and medium window (window to fa çade ratio of 30 and 60% respectively) with respect to the largest window, that is to say, the window to fa çade ratio of 90%. The blue lines represent the comparison of the small window while the red lines show the relative difference according to the medium size opening.

As can be seen, in the zone near the fa çade, the DA values produced by small windows correspond to 80% of those observed for the largest window, hence the small window promotes an increase of energy consumption close to 20% using an On/Off control system. In the case of the DAC metric, that difference is reduced up to 10%, therefore the dimming controls minimize the effect of the window size in the energy consumption in electric lighting.

B. Analysis of Room Reflectance

The second analysis studies the variation of daylight autonomy metrics depending on the reflectance of the room, considering that the location of the room is invariable.

Fig. 4 represents the relative difference of the analyzed dynamic metrics according to room reflectance. Three room depths are shown in the graph. The daylight autonomy comparison is shown in a solid line, while the continuous daylight autonomy is represented in a dash line.

The analysis is developed comparing the dark rooms with respect to the venues with a high reflectance values. The blue lines represent the comparison of the small window while the red and green lines show the relative difference according to the medium and large size opening.

As deduced from Fig. 4, the room reflectance barely affects to the energy consumption promoted by the smart controls in the zone near the façade. However, the dimming controls achieve a similar energy saving in the entire room.

C. Analysis of Room Location

The final trial studies the variation of daylight autonomy depending on the location of the room, considering that the window size and the room reflectance are invariable.

Fig. 5 represents the relative difference of the analyzed dynamic metrics according to room location. Three room depths are shown in the graph. The daylight autonomy comparison is shown in a solid line, while the continuous daylight autonomy is represented in a dash line.

The analysis is carried out comparing the London location (with poorer luminance conditions) with respect to Madrid and Stockholm. The blue lines represent the comparison with Stockholm while the red lines show the relative difference with regard to Madrid.

As seen in the previous figure, the location of the room is decisive to promote a suitable energy saving. The dimming systems, as in the previous trial, minimize the effect of the weather conditions, although the London location promotes a higher energy consumption than other studied locations.

VI. Conclusions

The comparison of the daylight dynamic metrics determines the effect of the architectural design in the energy saving promoted by lighting smart controls. As deduced from the trials above, the dimming systems minimize the impact of the room location and the reflectance of the inner surfaces, promoting a higher energy saving than the conventional On/Off system.

The quantification of the daylight autonomy metrics serve as a basis for the analysis of results. However, it also offers a database of the natural illumination produced by a window within a room. Accordingly, the most representative calculation models of current architecture have been chosen for simulation, using the most common window designs. Obviously, this research does not cover all possible hypotheses, but aims to show the most frequent cases study under the most adverse sky conditions.

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