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Dynamic analysis of office lighting smart controls management based on user requirements

Miguel Ángel Campano *, Ignacio Acosta, Samuel Domínguez, Remedios López-Lovillo

Instituto Universitario de Arquitectura y Ciencias de la Construcción, Universidad de Sevilla, Spain

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ABSTRACT

Daylight dynamic metrics provide an alternative approach for the assessment of the energy savings promoted by lighting control systems. This research aims to quantify the energy savings allowed by lighting smart controls using continuous and overcast daylight autonomy, novel metrics tested monitoring a mesh of illuminance-meters in test cells over a one-year period. Three types of smart controls are proposed, based on switches and dimmers, some of which were managed by illuminance-meters and irradiance detectors. Energy savings are assessed according to weather data, room dimensions, inner reflectances, window size and user requirements—illuminance needs and working hours. The results show a reduction in the average energy consumption of electric lighting of up to 23%, suggesting the suitability of the smart controls proposed. Smart controls without illuminance-meter feedback are only recommended for shallow rooms with low requirements, while dark deep rooms demand a complex dimming system managed by external illuminance-meters.

1. Introduction and objectives

1.1. Background

Lighting represents between 15 and 30% of the total energy consumption in buildings [1–5], so that its management is key for the promotion of smart energy consumption. Accordingly, the proper use of daylighting is an essential variable in reducing the energy consumption of electric lighting, through the passive design of the envelope of the building [6–9]. However, as architectural design is not usually enough to provide a noticeable energy saving, the development of new technologies, such as daylight-linked control systems [10], occupant detectors [11] and algorithms set by lighting software calculations [12,13] can help to reduce the impact on the environment.

The efficacy of lighting smart controls has been widely demonstrated in many instances. One of the first and most interesting cases is the New York Times Headquarters, where the dimming system linked to the occupancy detectors and the daylight availability results in a reduction of energy consumption of about 40% in the surface area near the façade [14]. Other noticeable examples can be observed for atriums [15,16] and office buildings [17,18], as well as other typologies [19,20], in which schedules [21,22], illuminance thresholds [23,24] and the effect of different dynamic control logics [12,25] were under analysis, showing converging results.

There are different approaches for the design of the lighting smart controls. The sensor-less system is based on the synchronization of the luminous flux provided by the lighting together with the solar path and the assumed sky luminance, determining the suitable dimming of the luminaires. This proposal provides a high energy saving [26], while the installation of illuminance-meters is not required. Moreover, the daylight-linked controls adjust the luminous flux of the luminaires by means of illuminance sensors located in the work plane and in the ceiling, providing a higher energy reduction in electric lighting [27], as the behavior of the luminaires can be determined according to the real measurement of daylighting. In addition, the daylight-linked system can be improved by including occupancy detectors [28] which can promote lower energy consumption. Based on the results observed in the aforementioned studies and many others [29–31], it can be stated that lighting smart controls can provide a noticeable increase of energy savings in electric lighting, reducing the power consumption by up to 50% when using dimming systems and close to 30% when using occupant detectors.

This prompts the question as to why lighting smart controls are not as widespread in architectural design today. According to several authors, the answer to this lies in the difficulties in installation, the effects of the placement of the illuminance-meters, the limitations of the predictive algorithms [32], and the stochastic behavior of occupants [33].

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* Corresponding author at: University of Seville, Instituto Universitario de Arquitectura y Ciencias de la Construcción, Universidad de Sevilla, 41012 Seville, Spain.
E-mail addresses: mcampano@us.es (M.Á. Campano), iacosta@us.es (I. Acosta).

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Glossary

ϕ	Luminous flux
CCT	Correlative Color Temperature
DA	Daylight Autonomy
DA_{con}	Continuous Daylight Autonomy
DA_o	Overcast Daylight Autonomy
DF	Daylight Factor
E_D	Daylight illuminance measured at a given point under real sky conditions
E_{Di}	Daylight illuminance measured by lux-meters under real sky conditions
E_R	Illuminance threshold
LED	Light-Emitting Diode
SPD	Spectral Power Distribution
t_i	Occupied time in the year
UDI	Useful Daylight Illuminance
w_{fi}	Weighting factor (which depends on the illuminance threshold)

Therefore, it is worth analyzing new proposals for lighting smart controls, reducing the impact of the installation inside the venue as well as the interaction of the occupants, respecting visual comfort in all cases.

Daylight-linked controls require the determination of different variables: window size and proportion are key for determining the energy saving obtained [34], as are the geometry of the room, the characteristics of the inner surfaces and the external weather conditions [20]. It is worth noting that two of the most important variables, the illuminance threshold for developing an specific task—with the possibility of incorporating the effect of lighting on the comfort level and on the circadian rhythm of users [35–39]—and the occupancy hours, have only been analyzed previously by a few authors [25,28,30,40–43], who concluded the noticeable effect of these variables.

Daylight dynamic metrics were established for the accurate calculation of the effect of the lighting smart controls, using lighting simulation software based on the daylight coefficient calculation, proposed by Tregenza et al. [44] and applied to the architectural context by Mardaljevic [45]. Unlike static metrics, such as the Daylight Factor, dynamic metrics consider statistical climate data based on a wide range of sky types [46]. One of the most widespread dynamic metrics is daylight autonomy (DA), proposed by the Association Suisse des Electriciens in 1989 and redefined by Reinhart et al. [47]. This metric is defined as the percentage of the year when a minimum illuminance threshold is met by daylight alone for a specific time frame. Accordingly, the higher the DA, the lower the energy consumption in electric lighting. Other dynamic metrics such as Useful Daylight Illuminance (UDI) [48] determine a useful range of daylighting, following the same calculation procedure.

Two main metrics have evolved from the origins of DA. The first, proposed by Rogers [47], is continuous daylight autonomy (DA_{con}), defined as the percentage of time throughout the year when a certain illuminance value is met by daylight, awarding a partial credit linearly to values below the threshold defined. This metric has rarely been used [49] despite its usefulness for determining the effect of a dimmer control, surely because its potential as a quantification tool for smart controls is not really well known. The second, proposed by Acosta et al. [50] in 2019, is overcast daylight autonomy (DA_o) which determines the percentage of the occupied time during which an illuminance threshold is met by daylight alone under the typical worst case scenario, overcast sky conditions. This metric can be used to quantify the impact of sensorless lighting controls in accordance with the predictive sky luminance.

In view of the above it becomes necessary to highlight the benefits of lighting smart controls, providing new approaches to extend their scope and employing the useful tools provided by the software calculations for quantifying the energy efficiency.

1.2. Aim and objectives

This study presents the assessment of new technologies for the smart control of electric lighting, quantifying the energy savings promoted by these novel proposals according to user requirements. Accordingly, this research takes into account the effect of the illuminance needs of the user as well as occupancy hours, considering other variables throughout the calculation process. The analysis carried out considers a test room with a variable depth, different window sizes and two reflectance values for the inner surfaces of the room. Weather conditions are also taken into account, assessing the performance of these smart controls in two locations with different average sky conditions.

The quantification of the energy saving allowed by these smart controls is determined by means of DaySim 3.1, a lighting simulation software developed by Reinhart et al. [51] based on the Radiance engine and on the daylight coefficients, and which provides the calculation for most of the daylight dynamic metrics. DA_o is determined following the procedure defined by Acosta et al. [50].

Three different types of smart controls are proposed, based on switches and dimmers, some of which are managed by illuminance-meters and irradiance detectors. Accordingly, DA, as well as DA_{con} and DA_o, provide information about the performance of the smart controls proposed, determining when the electric light should be dimmed or switched off using a light sensor or a scheduling algorithm. In order to provide an accurate analysis, the three metrics used for this research are checked under real sky conditions in a test room with similar characteristics to those observed in the calculation model. This complementary study is also shown in this manuscript. The novelty of this research is based on the following points:

- The smart controls proposed do not require any installation inside the room. Two of them use an exterior illuminance-meter and a pyranometer which measures the ratio between diffuse and global irradiance, defining the sky conditions, eliminating the need for light sensors inside the room. The third one uses the algorithms of minimum illuminance under overcast sky conditions to determine the minimum luminous flux of the luminaires in order to guarantee the required illuminance levels.
- Most of the literature relating to lighting smart controls considers different variables for the venue, such as the geometry of the room and the window. However, in some cases, the variation of the illuminance requirements and the occupancy hours are not taken into account in the assessment.
- The accuracy of the metrics which serve to determine the energy performance of the proposed controls, DA, DA_{con} and DA_o, is assessed in a test cell under real conditions. These three metrics have never been evaluated together before. In addition, DA_o is used for the first time to determine the energy saving of smart controls.

2. Methodology

2.1. Calculation protocol

Firstly, the calculation protocol is defined, in order to clarify the procedures described in the methodology that lead to the quantification of the energy efficiency provided by the studied lighting smart controls. Fig. 1 shows a flow diagram that describes the methodology carried out in this research. The first step addresses the definition of the lighting smart controls, as well as the dynamic metrics that describe the switching on or dimming behavior of each system. This correlation between dynamic metrics and smart controls is key for quantifying the energy efficiency of the studied systems. Subsequently, the simulation model which serves for the mentioned quantification, as well as other

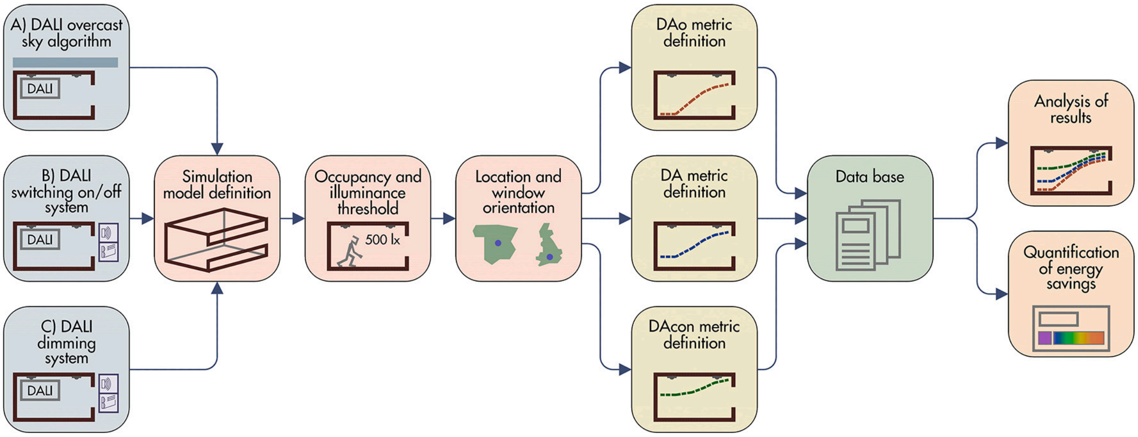

Fig. 1. Flux diagram of the calculation protocol.

calculation parameters, such as the user requirements and the lighting fixtures design, are defined. In parallel, a validation procedure confirms the accuracy of the calculation program, which is used to determine the dynamic metrics in the simulation model.

2.2. Definition of lighting smart controls

Three novel lighting control systems are proposed: System A is based on a DALI controller scheduled by an overcast daylight illuminance algorithm, System B uses a DALI controller with a pyranometer, an external illuminance-meter with the ability of switching the power supply and System C is composed by a DALI controller with a pyranometer, an external illuminance-meter with the ability of dimming the power supply.

These systems have been selected according to two conditions. Firstly, they do not require indoor sensors in the room, given that these devices are not usually properly located due to operational conditions, such as on the ceiling. In the case of the first system, it also does not have any outdoor measuring device, while the other two proposed systems rely on measuring devices outside to optimize the lighting system. The second condition is that the energy savings in electric lighting of the proposed systems must be quantified using the existing daylight dynamic metrics.

2.2.1. System A: DALI controller scheduled by overcast daylight illuminance algorithm

The first smart control proposed corresponds to a switching system for the luminaires controlled by the overcast daylight illuminance algorithm [50]. This procedure determines the minimum illuminance reached in the work-plane of the room, according to the daylight factors (DF) measured or simulated and the calculation of DA_o, which depends on this measurement, the elevation of the Sun and the luminance of the sky under overcast conditions. Accordingly, the luminaires switch on when the assumed daylight under overcast sky conditions is not high enough. This procedure guarantees an illuminance value equal to or higher than that required by the users, despite the fact that the real weather conditions could provide a higher luminance than that estimated by the algorithm. However, it is worth noting that this control does not require sensors for setting the luminous flux of the luminaires, making it an affordable system which can provide a noticeable energy saving. Moreover, this system does not allow the regulation of the luminous flux.

The energy savings promoted by this system can be determined by means of the analysis of DA_o results, calculating the percentage of time when the illuminance threshold is met by daylight under overcast sky conditions.

As shown in Fig. 2, system A can control the luminaire lines in different ways. Solution A1 is a control for the whole set of luminaires inside the venue, so that there is only one algorithm referring to the lower DF measured on the work-plane. Moreover, system A2 is a separate control for the luminaire line located near the façade and another one for the interior lines, requiring two DF measures, at the back of the room and at the end of the range of luminaire lines near the façade. Finally, system A3 shows separate controls for each luminaire line, requiring three DF values and one algorithm per measurement.

2.2.2. System B: DALI controller with pyranometer, external illuminance-meter and switching of electric supply

The second smart control proposed is based on the first one, but adds two external devices to characterize the real sky conditions. The pyranometer measures the global and diffuse irradiance of the sky vault, defining the sky conditions in accordance with the All-weather sky model defined by Perez et al. [52]. While the pyranometer serves to determine the luminance distribution of the sky, the external illuminance-meter allows the amount of light to be confirmed, knowing the solar path and the sky conditions. The data provided by both devices as well as the DF measurements determine the prediction of the illuminance values in the work-plane of the room.

As described in the background, DA [47] defines the percentage of time during the year when a certain illuminance is reached by daylight alone, considering real sky conditions. Therefore, this metric serves to determine the energy efficiency of this system.

The DALI controller switches the luminaire lines as in the previous case: system B1 adjusts the switching for all luminaires, solution B2 separately controls the line near the façade and those close to the back of the room and finally system B3 switches all luminaire lines independently, as described in Fig. 2. This procedure allows a better adjustment of the dynamic calculation to the real weather conditions and despite the fact that it requires the installation of outdoor sensors, it is still an affordable system, since it does not require illuminance-meters for setting the luminous flux of the luminaires. However, this system does not permit the regulation of the luminous flux either.

2.2.3. System C: DALI controller with pyranometer, external illuminance-meter and dimming electric supply

The third smart control is similar to the second one, albeit with a major difference. The pyranometer and the illuminance-meter provide information about the external lighting conditions, while the DF values allow the inner illuminance to be predicted. However, this smart control adjusts the luminous flux of the luminaires with a dimming system, providing a suitable amount of light when the illuminance threshold is not met.

As defined previously, DA_{con} determines the percentage of time throughout the year when an illuminance threshold is met by daylight,

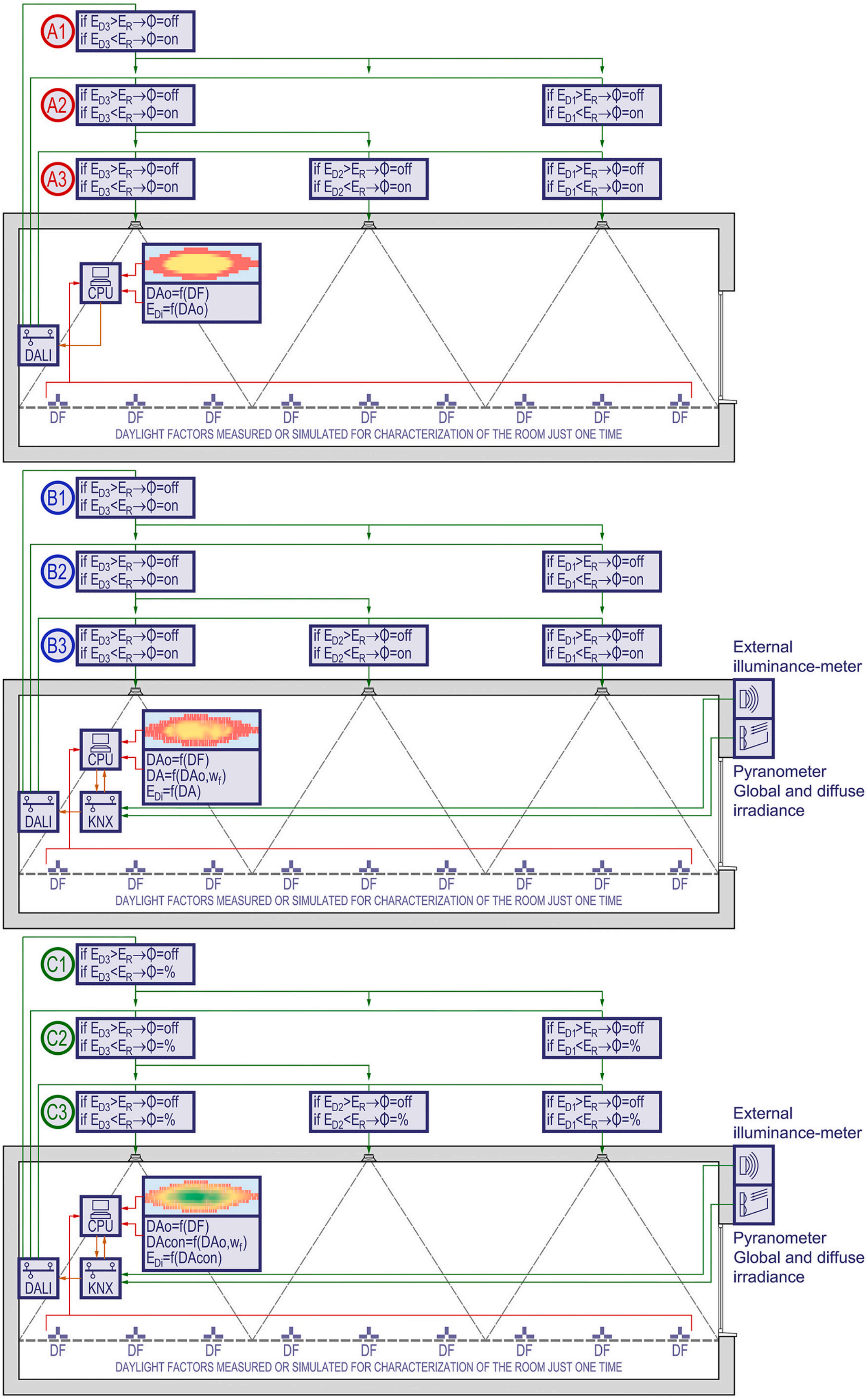

Fig. 2. Lighting Smart Controls proposed (Scenarios A, B and C with three different levels of luminaire line controls each, 1, 2 and 3).

awarding a partial credit linearly to values below the threshold defined. Therefore, this metric helps to assess the energy consumption of electric lighting allowed by this system.

As in the previous cases, three variants are considered for this smart control; system C1 dims all luminaires; solution C2 independently controls the line near the façade and the luminaires close to the back of the room; and finally system C3 shows separate controls for each luminaire line. This procedure, as in the case of the System B, also allows a better adjustment of the dynamic calculation to the real weather conditions, requiring the installation of the same lighting sensors on the outside. However, its dimming system permits the regulation of the luminous flux, improving the energy saving in electric lighting.

2.3. *Characteristics of the room model*

2.3.1. *Geometry of the room model*

The energy efficiency provided by the smart controls proposed is quantified by means of a calculation model defined using lighting simulation software DaySim 3.1. Subsequently, the metrics obtained are tested in a room under real sky conditions, in order to confirm the accuracy of this simulation tool. It must be also noted that certain variables, such as the effect of the human behavior in the interaction with the lighting system, cannot be considered by means of this simulation procedure.

As an example of a typical office room, a virtual space 3.00 m high with a variable depth is defined to calculate the daylight dynamic metrics mentioned above [53,54]. Walls, floor and ceiling are 0.25 m thick, considering a variable reflectance of the inner surfaces as well as a diffuse reflection. Window size, defined as a ratio of surface with respect to the façade, is variable. The window opening has a glass solar factor of 0.70. The measurement points are located 0.70 m above floor level with a spacing of 0.25 m between them. All the variables for this model are shown in Fig. 3.

Table 1 represents 18 room models defined in accordance with the geometry of the room, location, illuminance threshold and the time frame for the occupancy hours.

2.3.2. *Location and orientation of room models*

The assessment of the smart controls and the analysis of the impact of latitude and sky luminance are carried out in two different locations: London (UK) at 50° north latitude with predominantly overcast skies and Madrid (Spain) at 40° north latitude with mainly clear skies. Accordingly, the results shown for Madrid could be assumed for other locations with a Mediterranean climate, while the conclusions for London could be applied to Northern Europe. The weather data for these two locations were obtained from Energy Plus Engineering Reference [55], according to global and diffuse irradiance, using a pyranometer, and deducing the sky distribution from the sky model by Perez et al. [52] and accepted by the CIE [56].

All the openings in this research are north-facing and avoid direct sunlight, as this defines the worst case scenario for indoor daylight illuminance values [57,58].

2.3.3. *Lighting design of the room model*

According to previous calculations [22] and following the typical estimations for the energy efficiency of electric lighting, the energy consumption for bright rooms, with a high reflectance value of the inner surfaces, is considered to be 1.8 $W/m^2 \cdot 100$ lx, while for dark rooms this estimation increases up to 2.0 $W/m^2 \cdot 100$ lx, considering LED lamps with a correlative color temperature (CCT) of 4000 K. Both the variation of CCT and the type of luminaire can affect the final energy consumption, although the relative difference between the energy savings promoted by the smart controls mentioned above would be the same [59]. Fig. 4 represents the photometric diagram of the assumed lighting fixtures, as well as their placement in the ceiling, in order to justify the quantified energy efficiency values described above.

2.4. *User requirements*

This research considers two illuminance thresholds, as described previously in Table 1. The first one is 500 lx, a standard value for offices according to EN 12464–1:2012 [60], while the second is established as half that, 250 lx, which defines the lighting needs for a task requiring a

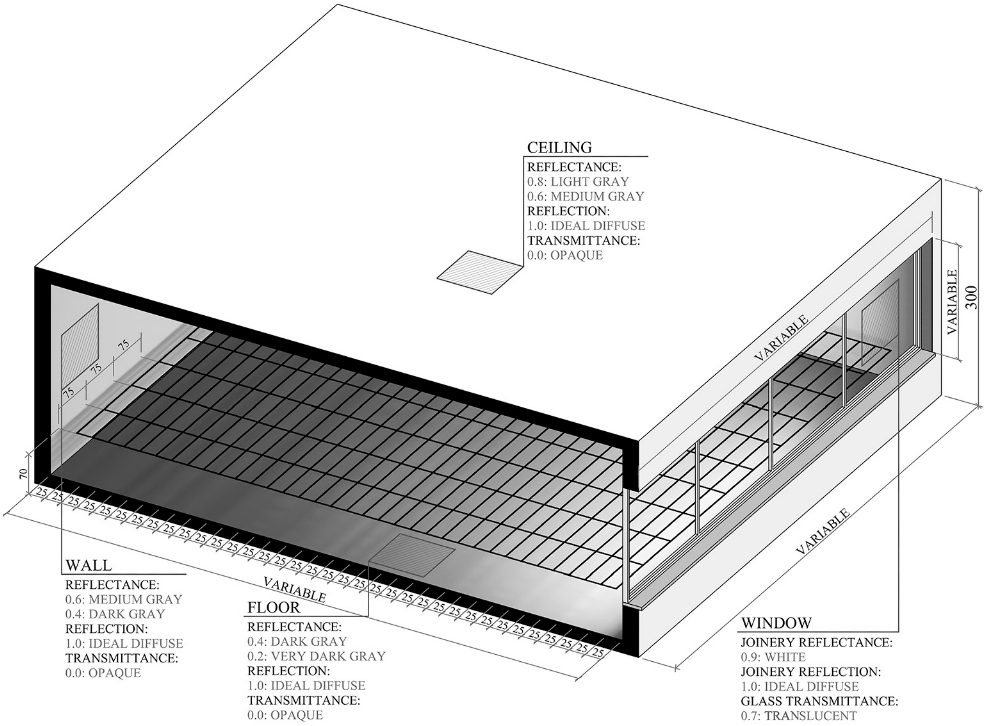

Fig. 3. Calculation model.

Table 1
Room models according to variables defined.

Model	Depth	WWR	Ceiling reflectance	Wall reflectance	Floor reflectance	Locations		Illuminance thresholds		Occupancy hours	
330B	3 m	30%	0.8	0.6	0.4	London (L)	Madrid (M)	**250**	**500**	**F**	**S**
360B	3 m	60%	0.8	0.6	0.4	London (L)	Madrid (M)	**250**	**500**	**F**	**S**
390B	3 m	90%	0.8	0.6	0.4	London (L)	Madrid (M)	**250**	**500**	**F**	**S**
330D	3 m	30%	0.6	0.4	0.2	London (L)	Madrid (M)	**250**	**500**	**F**	**S**
360D	3 m	60%	0.6	0.4	0.2	London (L)	Madrid (M)	**250**	**500**	**F**	**S**
390D	3 m	90%	0.6	0.4	0.2	London (L)	Madrid (M)	**250**	**500**	**F**	**S**
630B	6 m	30%	0.8	0.6	0.4	London (L)	Madrid (M)	**250**	**500**	**F**	**S**
660B	6 m	60%	0.8	0.6	0.4	London (L)	Madrid (M)	**250**	**500**	**F**	**S**
690B	6 m	90%	0.8	0.6	0.4	London (L)	Madrid (M)	**250**	**500**	**F**	**S**
630D	6 m	30%	0.6	0.4	0.2	London (L)	Madrid (M)	**250**	**500**	**F**	**S**
660D	6 m	60%	0.6	0.4	0.2	London (L)	Madrid (M)	**250**	**500**	**F**	**S**
690D	6 m	90%	0.6	0.4	0.2	London (L)	Madrid (M)	**250**	**500**	**F**	**S**
930B	9 m	30%	0.8	0.6	0.4	London (L)	Madrid (M)	**250**	**500**	**F**	**S**
960B	9 m	60%	0.8	0.6	0.4	London (L)	Madrid (M)	**250**	**500**	**F**	**S**
990B	9 m	90%	0.8	0.6	0.4	London (L)	Madrid (M)	**250**	**500**	**F**	**S**
930D	9 m	30%	0.6	0.4	0.2	London (L)	Madrid (M)	**250**	**500**	**F**	**S**
960D	9 m	60%	0.6	0.4	0.2	London (L)	Madrid (M)	**250**	**500**	**F**	**S**
990D	9 m	90%	0.6	0.4	0.2	London (L)	Madrid (M)	**250**	**500**	**F**	**S**

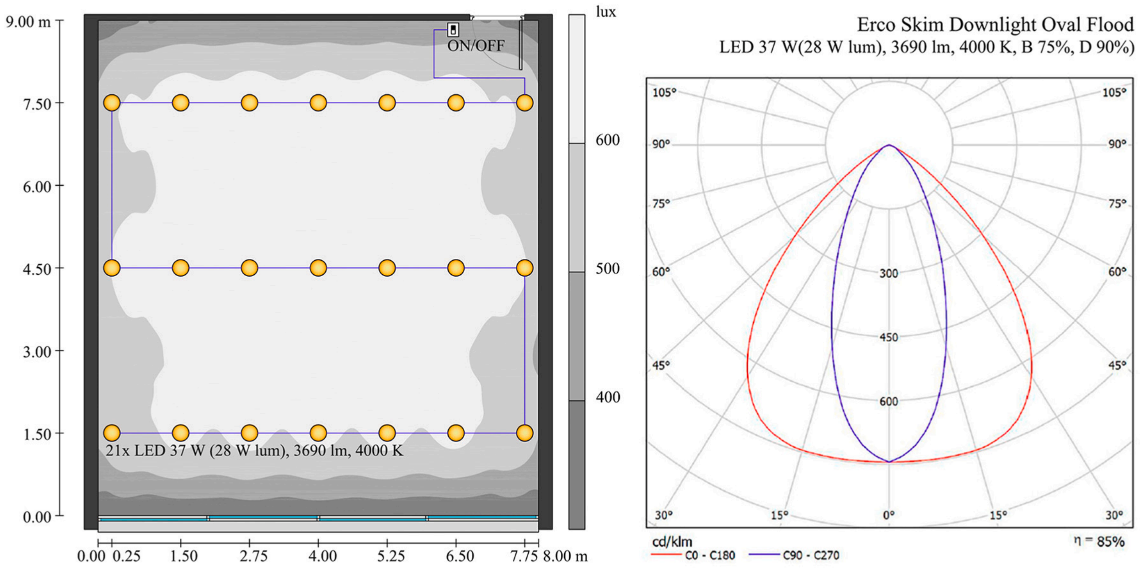

Fig. 4. Assumed placement of the lighting fixtures and photometric diagram of the luminaires.

medium visual effort. This second threshold allows a direct comparison of the studied dynamic metrics with the first one, since it corresponds to half that value. These illuminance requirements help to determine the suitability of the proposed lighting smart controls, in accordance with energy consumption. In any case, the energy efficiencies selected represent the most conservative scenario for calculating the suitability of smart controls.

Moreover, two time intervals are considered for occupancy hours. The first time frame for working hours is that of a full-time schedule, from 8:00 am to 6:00 pm. The second time interval is set from 8:00 am to 2:00 pm, representing a typical short-time schedule.

2.5. Parameters of the calculation program

The assessment of the dynamic metrics used in this research, linked to the smart controls proposed in the calculation model, is carried out using lighting simulation program DaySim 3.1, which is based on the Radiance engine, developed by the Building Technologies Department at the Lawrence Berkeley National Laboratory and validated in several studies [51,61,62]. Table 2 shows the calculation parameters used by this program in this study.

Table 2
Parameters of the calculation program [64,65].

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

It must be noted that, despite the fact that numerous papers have validated this simulation tool, Radiance engine can be less accurate in complex architectural scenarios [63], thus a subsequent validation is carried out to confirm the usefulness of this program, using a real test cell with a similar configuration to that observed in the simulation room.

2.6. Calculation metrics

2.6.1. Daylight autonomy (DA)

As described above, DA represents the percentage of the year when a minimum illuminance threshold is met by daylight alone for a specific occupancy time [47]. Accordingly, the higher the DA, the lower the energy consumption in electric lighting.

This metric can be defined as eq. (1):

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

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

As can be deduced, this metric makes it possible to determine the time during which the luminaires need to be switched off, which helps to quantify the energy savings promoted by the proposed smart control B. This corresponds to a DALI controller which switches the electric supply of the luminaires on and off according to the real sky conditions measured using the pyranometer and the external illuminance-meter.

2.6.2. Continuous daylight autonomy (DA_{con})

The second dynamic metric used in this research is DA_{con}, which represents the percentage of the year when a certain illuminance threshold is achieved by daylight alone, awarding a partial credit linearly to the values below the defined threshold [47]. Accordingly, this metric can be expressed as eq. (2):

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

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_R is the illuminance threshold.

As deduced, DA_{con} makes it possible to quantify the percentage of time during which the luminaires must be switched off or in contrast how much the luminous flux should be increased to provide enough illuminance. Accordingly, this metric serves to determine the energy savings obtained by smart control C, defined as a DALI controller which dims the luminous flux of the lighting depending on the real sky conditions measured by the external devices.

2.6.3. Overcast daylight autonomy (DA_o)

The third metric applied in this research is DA_o, which determines the percentage of the occupied time during which an illuminance threshold is met by daylight alone under the typically worst case scenario, overcast sky conditions [50]. This metric can be expressed as follows (3):

$$DA_o = \frac{\sum_i wf_i \cdot t_i}{\sum_i t_i} \in [0,1] wf_i = \begin{cases} 1 \text{ if } E_{DO} \geq E_R \\ 0 \text{ if } E_{DO} < E_R \end{cases} \qquad (2)$$

where t_i is the occupied time in a year, wf_i is the weighting factor which depends on the illuminance threshold, E_{DO} is the daylight illuminance measured at a given point under overcast sky conditions, and E_R is the illuminance threshold.

As expressed in the previous definition, this metric does not depend on the real sky conditions, so it acts like DA, but considering a continuous overcast sky. Therefore, DA_o can be used to quantify the impact of sensor-less lighting controls, in accordance with the predictive sky luminance, as defined in the case of smart control A.

3. Validation of the calculation program and the dynamic metrics

The reliability of the dynamic metrics and of the simulation tool is verified through a validation process, performed in this study by comparing computational results and experimental trials completed with a test cell [66]. Accordingly, this validation provides realistic results for the studied dynamic metrics.

3.1. Characteristics of the test cell and the computational model

The test cell used for the experimental trials [67] is located in Seville, Spain. This south-facing room, which is 2.40 m wide, 3.20 m deep and 2.70 m high, has a lightweight enclosure attached to a steel frame consisting of white high-density polyurethane sandwich panels, including the floor and the roof. This inner envelope has a reflectance of 0.72 for walls and ceiling and 0.22 for the floor. A single window, 108 cm high by 116 cm wide, with 4.8.4 double glazing and a solar factor of 0.75 is found in the south-facing façade.

Illuminance was measured inside the cell at ground level throughout 2017 (hourly tendency from measurements performed each 5 min) with 8 Delta Ohm HD 2021 T illuminance-meters (range of 20–2000 lx, accuracy of ±3.0%), spaced 0.40 m apart on the longitudinal axis of symmetry of the cell, as can be seen in Fig. 5A. These sensors were emulated in the simulation model through an overlaid calculation grid. The exterior illuminance was measured with a Delta Ohm LP PHOT 02 AC Photometric probe (0–200,000 lx ±9.0%) and the weather conditions considered are those corresponding to Seville (Spain), with Latitude 37.42°, Longitude 5.40° and mainly clear skies.

3.2. Initial conditions for the comparison process

The occupancy schedule for the calculation of DA, DA_{con} and DA_o, both in the case of the measurements and the simulation model, was defined from 8:00 am to 6:00 pm [66], following the working hours defined in the methodology for full-time occupancy. Two illuminance thresholds were established for the dynamic calculations, 250 and 500 lx, in accordance with the user requirements described in the previous section.

3.3. Results of the comparison process

Fig. 5B and C show the DA, DA_{con} and DA_o values calculated through two graphs, one for each of the illuminance thresholds—250 and 500 lx—, comparing the dynamic results from measurements and the computational model.

DA values from simulations are close to those obtained by measurements, showing the highest maximum deviation for a threshold of 500 lx (8.4%) close to the window, as well as moderate divergences between simulations and measurements around 6% at the study points furthest from the window. Divergences in DA_{con} values are lower than those from DA and show the maximum deviation of 3.8% for 500 lx.

Values of DA_o, correlated with the measured/simulated DF, show a maximum deviation of 9.1% for a threshold of 250 lx (0.6 m from the window), below 10%, but show no relevant results for 500 lx, as the combination of the high illuminance threshold and the low values of DF obtained results in DA_o values close to 0—a DA_o simulation value of 8% for a DF of 3.0% and a DA_o measurement value of 1% for a DF of 2.8%.

Thus, the bias error shown with a threshold of 250 lx for these three metrics is 3.0% in the case of DA, 0.9% for DA_{con}, and 0.1% for DA_o (1.0% for DF), obtaining a standard deviation (95% reliability) of 8.3% for DA, 3.9% for DA_{con}, and 9.5% for DA_o (0.96% for DF). All these deviations —divergences, bias errors and standard deviations—are below 10% and therefore acceptable. It can thus be concluded that DaySim 3.1 accurately calculates DA, DA_{con} and DA_o daylighting dynamic metrics in spaces with similar boundary conditions. Accordingly, this validation confirms the usefulness of the calculation program defined in the methodology and its suitability for the calculation of the energy savings provided by the smart controls proposed.

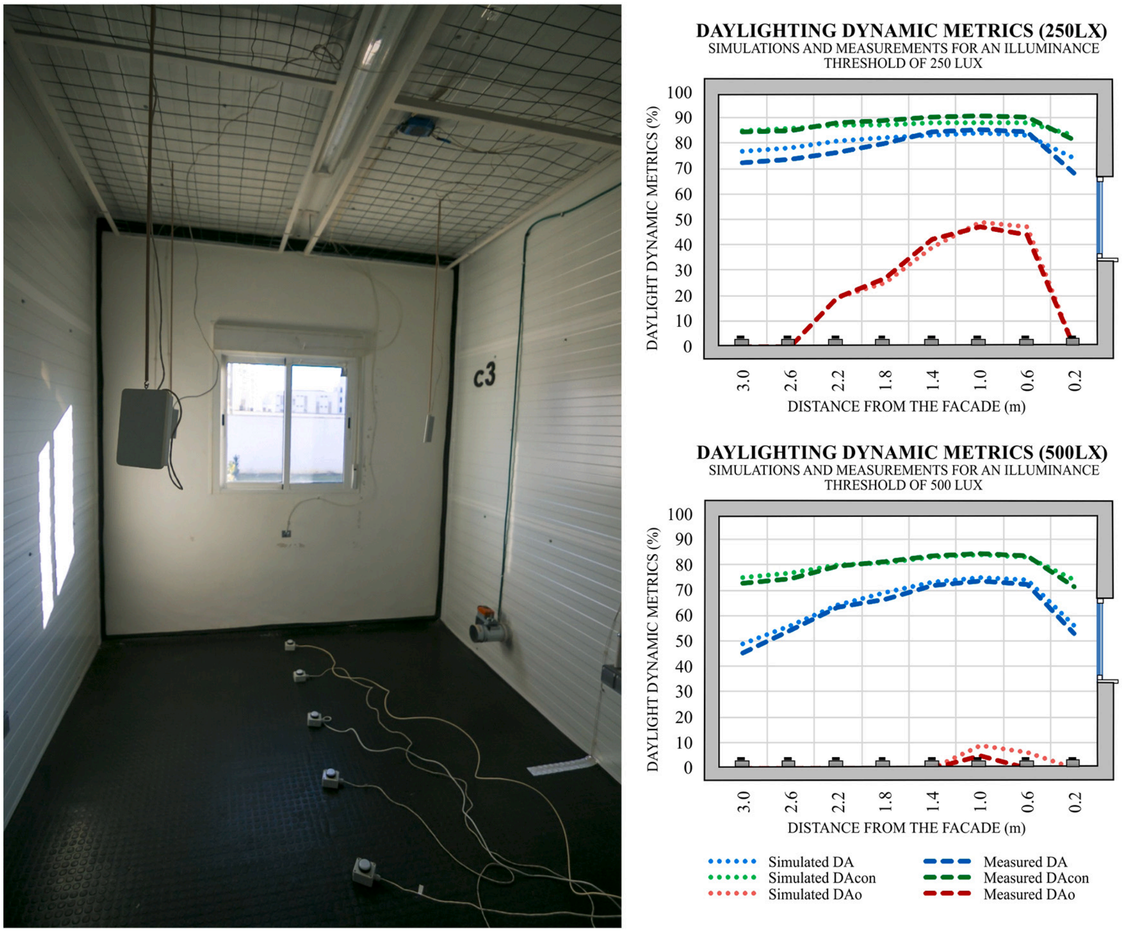

Fig. 5. Test cell used for the comparison trials. (A) Test cell with the array of illuminance-meters above the floor. (B) and (C) DA, DA_{con} and DA_o results obtained from simulation calculations and illuminance measurements for 250 and 500 lx.

4. Results

The results of this study are structured into several analyses, deducing the impact of the geometry of the room (window size and room depth); the influence of the characteristics of the inner environment (light or dark inner surfaces); the effect of the average weather conditions (Madrid or London); and finally the impact of user requirements.

4.1. Analysis of smart controls according to room geometry

The first analysis carried out assessed the impact of the smart controls proposed on the energy savings according to window size and room depth. Based on the variables defined in the methodology, Fig. 6 shows the model sections for Madrid, defining the quantification of the dynamic metrics—which serve to determine the performance of the 3 types of smart controls proposed depending on room geometry. Subsequently, Fig. 7 shows the same sections for the London location. These sections also show the average energy consumption measured in the central axis, considering a lighting consumption for bright rooms of 1.8 $W/m^2 \cdot 100$ lx and for dark rooms of 2.0 $W/m^2 \cdot 100$ lx, as described in the methodology.

The variables analyzed in Figs. 6 and 7 correspond to the depth of the room and the window-to-wall ratio, so that the first column represents rooms 3.00 m deep, the second one rooms 6 m deep, and the last column shows rooms 9.00 m deep. Moreover, the first row refers to rooms with a window-to-wall ratio of 30%, the second row 60% and the last row shows rooms with a window size of 90% with respect to the façade area. In this particular analysis, the sections shown correspond to the requirements of 500 lx and full-time schedule.

Analysis of these sections shows that smart control A, defined by a switching system controlled by the DA_o algorithm, would only be advantageous in shallow rooms with large openings—equal to or larger than 60%—given that this affordable system with minimal installation requirements provides a noticeable energy saving—higher than 50%—in these scenarios. In the rest of the cases, this solution does not allow optimum energy efficiency, except in the zone near the façade.

Moreover, smart control B, relating to the DA metric and defined by a switching system controlled by a pyranometer and an external illuminance meter, produces a noticeable reduction in the energy consumption in electric lighting with respect to the aforementioned control for the specific cases of deep rooms—with a depth of between 6 and 9 m—with a sufficient window size larger than 30%. Quantifying the previous statement for the case study of Madrid, as seen in Fig. 6, control B allows an absolute increase in energy savings of up to 71% for 6 m deep rooms and between 22 and 55% for 9 m deep rooms, depending on the window size. Analyzing the London scenario, the difference between the performance of controls A and B is lower, as the most predominant overcast sky of this scenario converges with the assumption defined by the DA_o algorithm. As deduced from Fig. 7, the absolute increase in energy savings promoted by control B reaches around 41% for 6 m deep rooms and up to 24% for deeper spaces.

It should also be noted that control C, consisting of a pyranometer, an external illuminance meter and a dimming system offers better results in deep rooms compared with the previous systems, providing an absolute increase in energy saving with respect to system A of between 66 and 84% for rooms 6 m deep and between 32 and 78% for rooms 9 m deep in

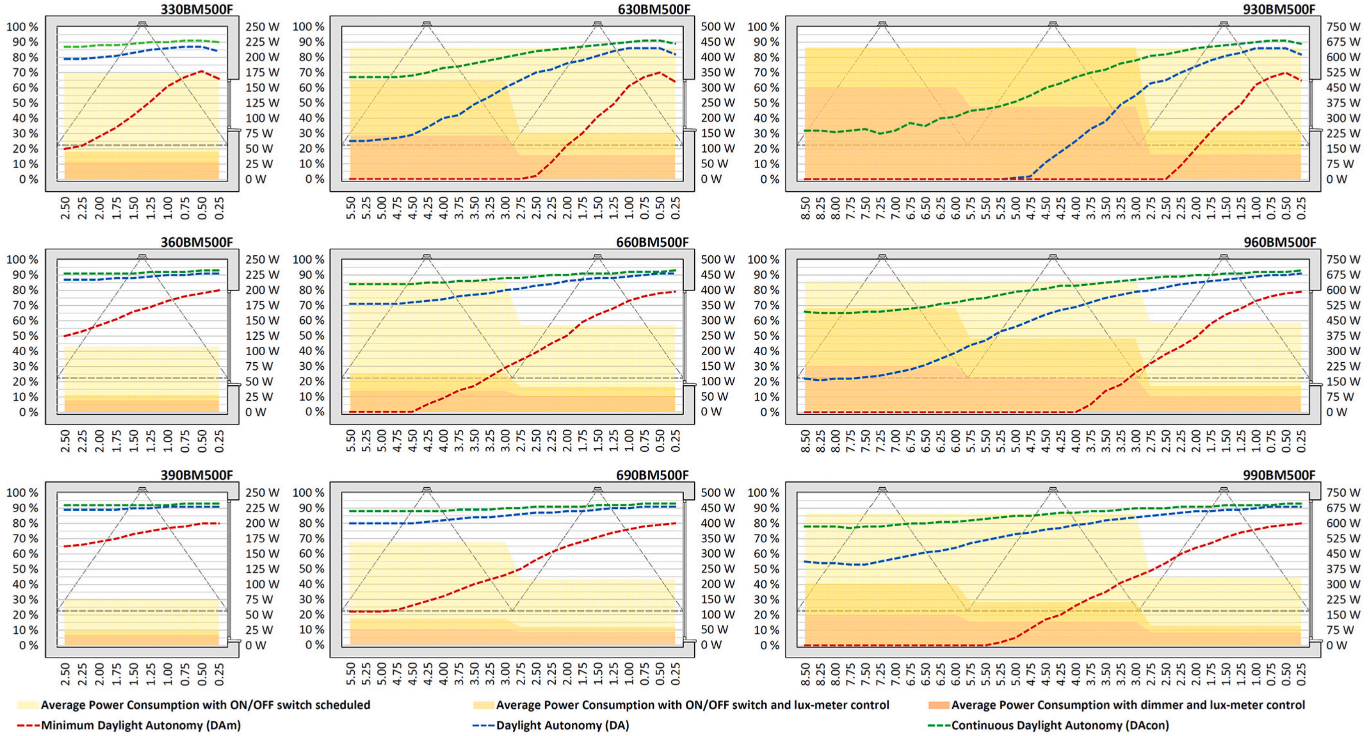

Fig. 6. Analysis of room depth: Room models for Madrid location with variable depth and window size and requirements for full-time frame at 500 lx. The primary Y-axis shows the percentage obtained for the three dynamic metrics, while the secondary Y-axis shows the average power consumption for each of the three solutions of the systems proposed.

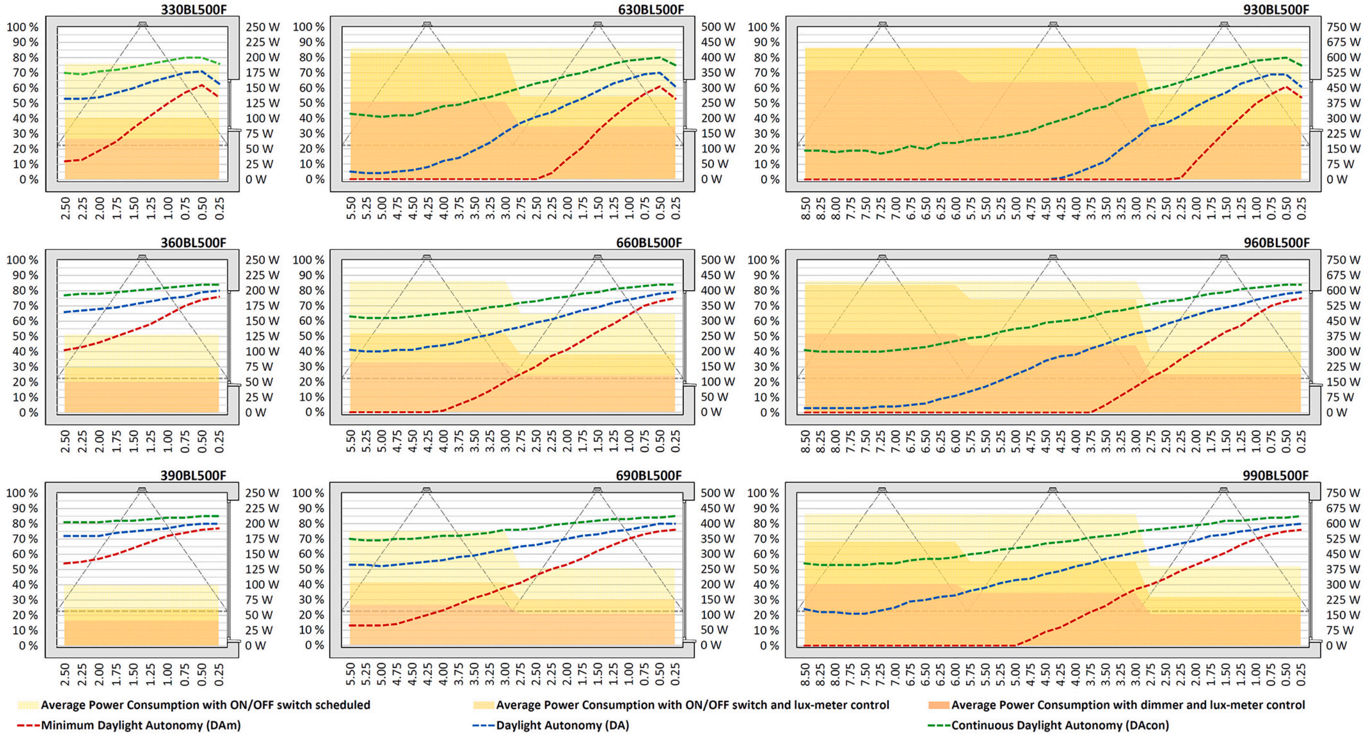

Fig. 7. Analysis of window size: Room models for London location with variable depth and window size and requirements for full-time frame at 500 lx. The primary Y-axis shows the percentage obtained for the three dynamic metrics, while the secondary Y-axis shows the average power consumption for each of the three solutions of the systems proposed.

the Madrid case study location. As deduced from Fig. 7, this benefit is slightly lower for the London scenario, with worse sky conditions and therefore a poorer use of daylighting, where the absolute increase of energy saving promoted by the dimming system ranges between 19 and 54% for deep rooms.

The divergence between controls C and B is lower than that of system A, as both systems are based on real sky measurements, with the only difference that system C uses a dimmer instead of a switch. In this scenario, the absolute increase in energy savings promoted by the dimming control with respect to the switches ranges between 8 and 42% in the case of Madrid and between 17 and 30% for the London location, depending on room depth and window size.

4.2. Analysis of smart controls according to room reflectance

The second analysis determines the effect of the reflectance of the inner surfaces of the room on the performance of the smart controls proposed, and two scenarios are set up as defined in the methodology: bright or dark surfaces. Fig. 8 shows the daylight dynamic metrics, which define the performance of the lighting controls, in cross-sections with a variable window size and different reflectance values for the inner surfaces of a room with a depth of 6 m. The first column represents bright and dark rooms with small windows, the second one rooms with medium-sized openings, and the last one, rooms with large windows. The first row shows rooms with a high reflectance value for the inner surfaces while the second row corresponds to those with low reflectance. Although this study is carried out on the full sample of room models, Fig. 8 shows the results considering the Madrid location, an illuminance threshold of 500 lx and a full-time schedule.

Comparing rooms with the same geometry and different reflectance values it can be deduced that dark rooms with small windows require a type C smart control, with a dimmer which adjusts the luminous flux depending on external conditions, given that controls A and B are not really advantageous for these scenarios, irrespective of room depth. As seen in Fig. 8, DA_o and DA, the metrics which define the energy savings provided by smart controls A and B respectively, drop to zero in the area close to the back of the room.

In the case of a dark room 6 m deep with a medium-sized or large opening—window-to-wall ratio between 60 and 90%—, the absolute increase promoted by control C with respect to B ranges between 18 and 35% for the Madrid location and between 25 and 38% for London, depending on the window size. The difference between both systems is similar in most of the cases for dark rooms with a depth of 6 m. Accordingly, system B could be advantageous only for rooms with a window larger than 60% of the façade surface.

It should be also noted that, considering the scenario of rooms with a low reflectance, control A is not suggested, except in the cases of spaces with large windows—window-to-wall ratio of 90%—with an independent control of the luminaire lines.

4.3. Analysis of smart controls according to location of the room

The third study quantifies the impact of the room location in the performance of the smart controls proposed, following the methodology described above. Fig. 9 shows cross-sections defining the daylight dynamic metrics related with the daylight-linked controls and the average energy consumption for the Madrid and London locations. All sections correspond to rooms with a depth of 6.00 m, with different window sizes shown in the columns. The first two rows correspond to the Madrid models and the second two to the London models, the first and third of which consider requirements of 500 lx while the second and fourth consider a threshold of 250 lx and a short-time schedule.

As deduced from Fig. 9, considering the scenario of London, with mainly cloudy skies, it can be observed that there is a high convergence of the dynamic metrics in the area near the façade, that is to say, the performance of all smart controls is similar except in the back of the rooms, where the performance of control A clearly diverges from that of controls B and C. Moreover, in relation to the case of Madrid, with predominant clear skies, a higher difference of the measured values can be observed for all metrics in the entire room. Therefore, it can be concluded that the impact of the smart controls studied is lower for locations with mainly overcast sky conditions. In order to quantify the previous statement, it can be observed that smart controls in a room located in Madrid provide an absolute increase of up to 25% irrespective of window size, due to advantageous higher sky luminance. This difference between both locations notably increases in the area near the back of the room.

4.4. Analysis of smart controls according to user requirements

The final and most innovative analysis corresponds to the effect of user requirements. Fig. 10 represents the cross-sections of the deeper rooms with medium-sized window, determining the average energy consumption in electric lighting and the dynamic metrics which serve to

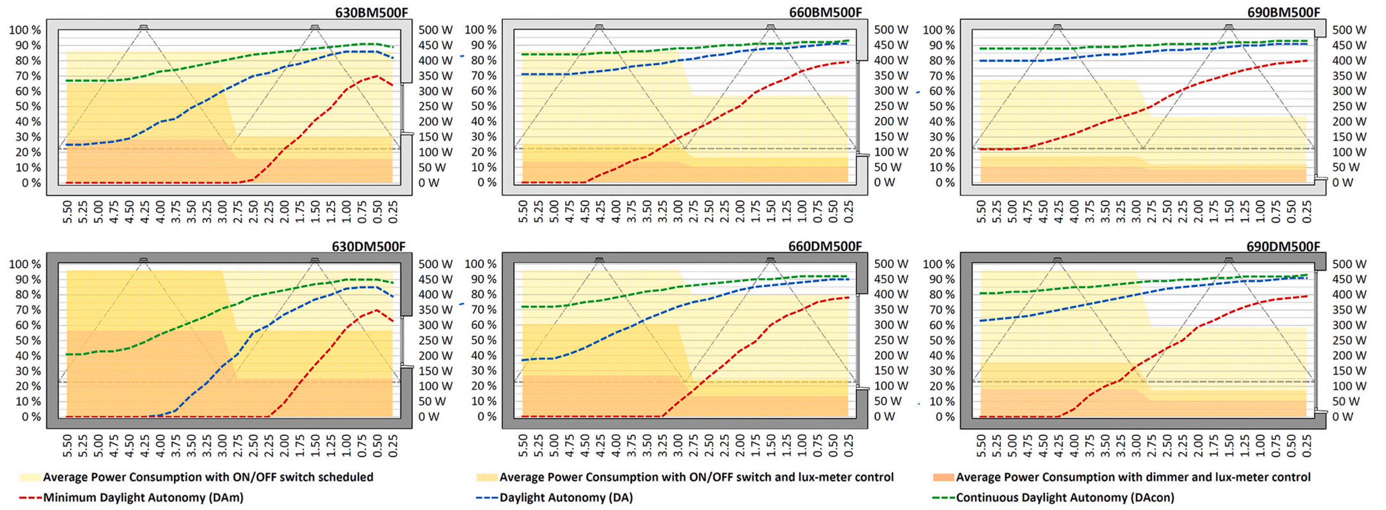

Fig. 8. Analysis of room reflectance: Room models for Madrid location with variable reflectance and window size and requirements of full-time frame at 500 lx. The primary Y-axis shows the percentage obtained for the three dynamic metrics, while the secondary Y-axis shows the average power consumption for each of the three solutions of the systems proposed.

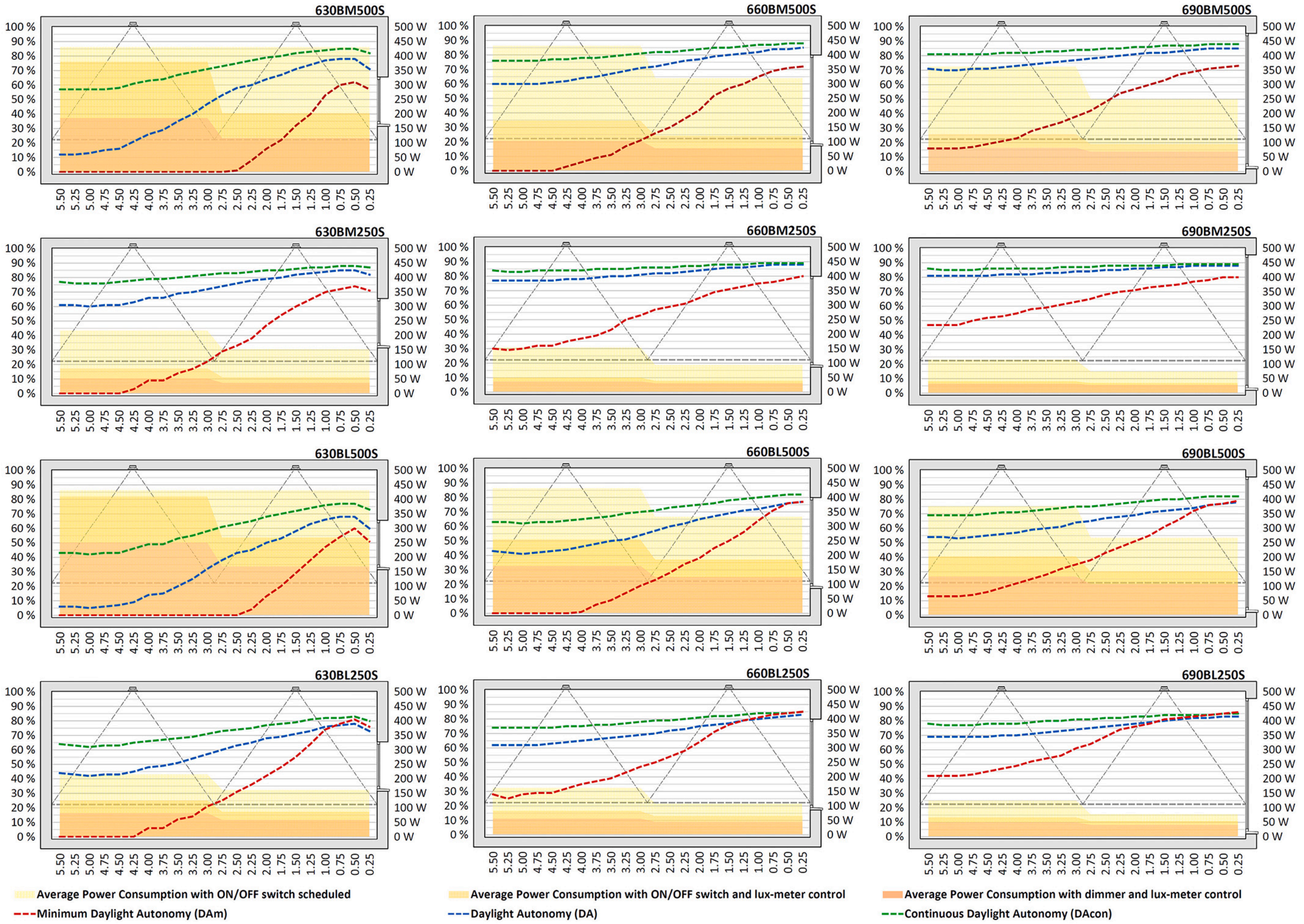

Fig. 9. Analysis of room location: Room models for Madrid and London locations with a variable window size and requirements of short-time frame at 500 lx and 250 lx. The primary Y-axis shows the percentage obtained for the three dynamic metrics, while the secondary Y-axis shows the average power consumption for each of the three solutions of the systems proposed.

estimate the energy savings promoted by the proposed systems. The first column shows the Madrid sections while the second represents the rooms in the London location. Of the rows, the first two relate to requirements of 500 lx, with the first examining a full-time schedule and the second a short-time schedule. The last two rows show the requirements of 250 lx, defining full-time in the third row and short-time in the last one. Despite the limited results shown in Fig. 10, all models are assessed in this analysis, considering the combination of all variables.

Analyzing the working hours, it can be observed that for the London location—with mainly cloudy skies—there is no noticeable influence of the occupation time in the performance of the smart controls studied, taking into account all scenarios. The opposite occurs in Madrid—with mainly clear skies—where it can be observed that, in the case of smart controls B and C, full-time schedules promote an absolute increase in energy savings of up to 15% with respect to short-time ones, irrespective of the illuminance threshold.

Moreover, the illuminance threshold has a remarkable influence on the performance of the smart controls analyzed. This impact, as seen in Fig. 10, is almost inversely proportional to the window size, so the lower the daylight access, the higher the performance of the smart controls for low-illuminance requirements. Quantifying this assertion for the specific case of Madrid, the maximum absolute difference between the thresholds of 250 and 500 lx is 39% for system A, 49% for system B, and 31% for system C. In the case of an average overcast scenario, such as the London location, the difference of the performance of the smart controls for the illuminance thresholds proposed is lower due to the higher dependence on electric lighting irrespective of the light required. In the London case study, the absolute difference between the thresholds of 250 and 500 lx is 32% for system A, 38% for system B, and 21% for system C. Accordingly, it is important to adjust the illuminance levels to the required task, particularly in mainly clear sky locations, taking into account that the energy savings promoted vary depending on the smart control used, the access to daylight, and depth of the room.

5. Quantification of energy efficiency

5.1. *Quantification of energy savings in Madrid*

In accordance with the results obtained, described in the section above, Tables 3 to 5 summarize the average energy saving promoted by the proposed lighting smart controls for the Madrid location. Each table represents a room model with a specific depth. The columns are arranged depending on window size, room reflectance and user requirements, defined by the occupancy hours and the illuminance threshold. The rows show the smart controls proposed, defining if they are controlling one or several groups of luminaires independently. From the results shown, the average energy saving, measured in kWh/m^2·year, determines the suitability of each smart control depending on a given scenario, so that the higher the energy saving, the more suitable the lighting system. In order to facilitate the reading of the tables—as well as the tendency of the energy savings depending on each studied

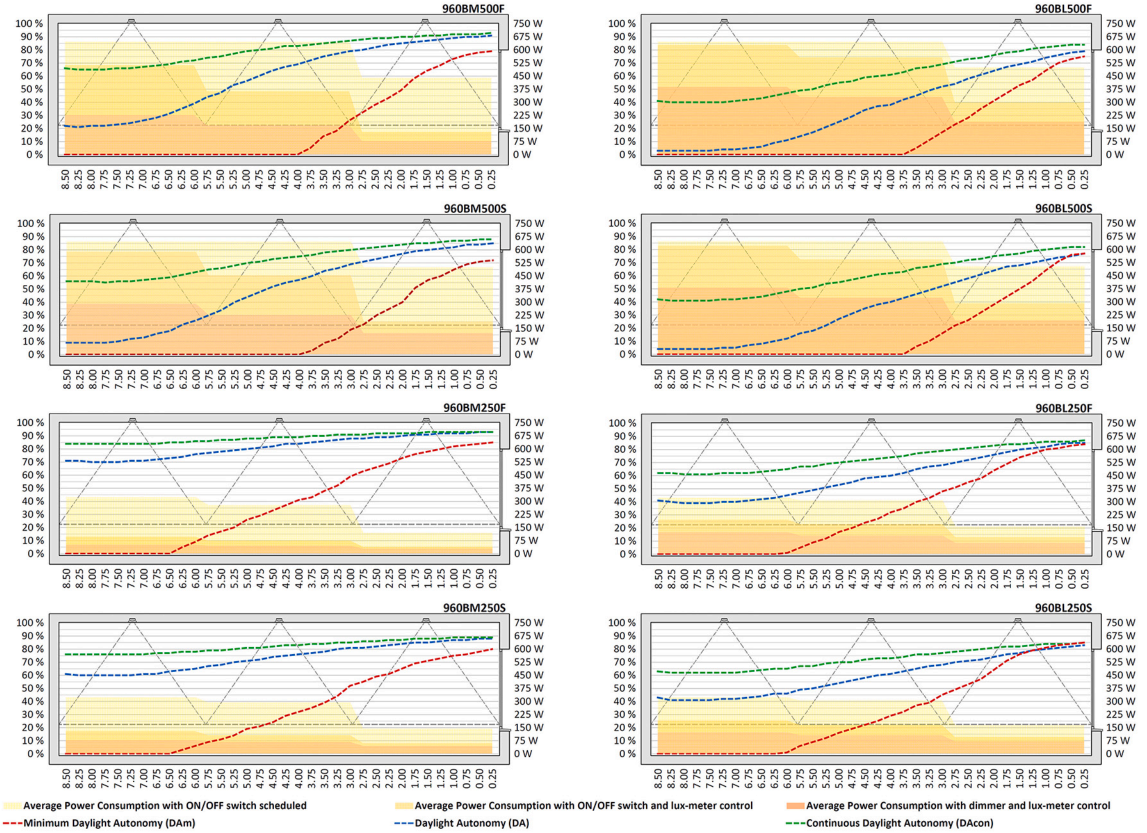

Fig. 10. Analysis of user requirements: Room models for Madrid and London locations with requirements of full-time and short-time frame at 500 lx and 250 lx. The primary Y-axis shows the percentage obtained for the three dynamic metrics, while the secondary Y-axis shows the average power consumption for each of the three solutions of the systems proposed.

Table 3
Average energy savings measured in kWh/m^2·year for rooms located in Madrid with a 3 m depth.

Smart Control proposed	WWR	30%								60%								90%							
	Room reflectance	High				Low				High				Low				High				Low			
	Occupancy hours	Short T.		Full T.		Short T.		Full T.		Short T.		Full T.		Short T.		Full T.		Short T.		Full T.		Short T.		Full T.	
	Groups / Illuminance	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500
Smart Control A	1 group	3.2	2.0	6.3	4.7	2.3	0.0	5.1	0.0	4.6	5.9	8.5	11.7	4.4	4.2	8.5	9.1	5.0	8.1	9.1	15.2	5.1	6.9	9.6	13.5
Smart Control B	1 group	5.7	9.7	10.3	18.5	5.9	8.7	11.1	17.9	6.0	11.2	10.6	20.4	6.4	11.5	11.6	21.6	6.0	11.5	10.8	20.8	6.6	12.3	11.7	22.6
Smart Control C	1 group	6.0	11.2	10.6	20.4	6.5	11.7	11.7	21.6	6.2	11.9	10.8	21.3	6.7	12.8	12.0	23.1	6.2	12.1	10.9	21.5	6.8	13.3	12.0	23.4

parameter—colors labeled to each measure represents the suitability of that value, being green the best value and red the worst, drawing a gamut range between both colors.

As deduced from Tables 3 to 5, smart control C is an optimal solution for deep rooms, while systems B and C could be considered appropriate solutions for rooms with depths of 6 and 3 m respectively, providing a minimum energy saving of 4 kWh/m^2·year. This is true for rooms with a large enough opening size, that is to say, a window-to-wall ratio larger than 30%.

A comparison of energy savings shows no noticeable difference between a smart system which controls two or three luminaire lines, as seen in Table 5. Accordingly, in all cases the lighting system must consider an independent management of the luminaire line near the façade, while the fixtures placed in the center and back of the room must be controlled in at least one group.

5.2. *Quantification of energy savings in London*

As described in the previous section, Tables 6 to 8 quantify the average energy saving allowed by the smart controls described in the methodology for the London location. As in the previous case, each table represents a room depth. The columns show the results according to window size, room reflectance and user requirements, while the rows establish the smart controls proposed, defining whether they are

Table 4
Average energy savings measured in kWh/m^2·year for rooms located in Madrid with a 6 m depth.

Smart Control proposed	WWR	30%								60%								90%							
	Room reflectance	High				Low				High				Low				High				Low			
	Occupancy hours	Short T.		Full T.		Short T.		Full T.		Short T.		Full T.		Short T.		Full T.		Short T.		Full T.		Short T.		Full T.	
	Groups / Illuminance	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500
Smart Control A	1 group	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.1	0.0	4.6	0.0	0.2	0.0	0.7	0.0	3.3	2.2	6.4	5.1	1.6	0.0	3.8	0.0
	2 groups	1.0	0.0	2.2	0.0	0.4	0.0	1.1	0.0	3.1	1.8	6.0	4.0	1.8	0.9	3.6	2.2	3.9	4.1	7.5	8.4	3.1	2.3	6.2	5.1
Smart Control B	1 group	4.3	1.7	8.4	5.9	2.0	0.0	5.2	0.0	5.4	8.4	9.9	16.6	5.1	3.4	9.9	9.6	5.7	10.0	10.3	18.7	5.8	8.0	10.7	16.4
	2 groups	4.7	4.6	9.1	10.5	3.6	2.0	7.6	5.3	5.6	9.3	10.1	17.8	5.6	6.6	10.6	14.6	5.8	10.5	10.4	19.4	6.1	9.7	11.1	18.9
Smart Control C	1 group	5.4	7.7	9.8	15.4	4.9	4.6	9.8	10.7	5.9	10.4	10.4	19.3	6.1	9.8	11.2	19.1	6.0	11.2	10.6	20.4	6.4	11.4	11.6	21.2
	2 groups	5.6	9.1	10.1	17.4	5.5	7.6	10.4	15.0	6.0	11.1	10.6	20.1	6.4	10.9	11.4	20.5	6.1	11.6	10.7	20.8	6.6	12.1	11.8	22.1

Table 5
Average energy savings measured in kWh/m^2·year for rooms located in Madrid with a 9 m depth.

Smart Control proposed	WWR	30%								60%								90%							
	Room reflectance	High				Low				High				Low				High				Low			
	Occupancy hours	Short T.		Full T.		Short T.		Full T.		Short T.		Full T.		Short T.		Full T.		Short T.		Full T.		Short T.		Full T.	
	Groups / Illuminance	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500
Smart Control A	1 group	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	2.0	0.0	0.0	0.0	0.0	0.0
	2 groups	0.6	0.0	1.4	0.0	0.4	0.0	0.9	0.0	1.3	1.1	2.5	2.5	1.1	0.6	2.2	1.5	2.0	1.9	4.1	3.8	1.5	1.6	2.9	3.3
	3 groups	0.6	0.0	1.4	0.0	0.4	0.0	0.9	0.0	1.5	1.1	3.0	2.5	1.1	0.6	2.2	1.5	2.4	1.9	4.8	3.8	1.5	1.6	2.9	3.3
Smart Control B	1 group	0.4	0.0	1.9	0.0	0.0	0.0	0.0	0.0	4.3	1.3	8.3	5.1	1.2	0.0	3.6	0.0	5.0	5.9	9.4	12.9	3.7	0.0	7.7	0.3
	2 groups	2.0	2.3	4.4	4.9	1.7	1.3	3.4	3.6	4.8	4.2	9.0	9.7	2.8	3.2	6.2	6.4	5.3	7.5	9.8	15.2	4.6	3.7	8.9	7.3
	3 groups	2.6	2.3	5.6	4.9	1.8	1.3	3.4	3.6	4.9	5.1	9.2	11.4	3.5	3.2	7.4	6.4	5.4	8.2	9.9	16.1	4.9	4.5	9.5	9.7
Smart Control C	1 group	3.7	3.8	7.4	7.5	2.0	2.0	4.2	4.2	5.3	7.9	9.8	15.4	4.6	4.7	9.0	9.6	5.7	9.8	10.3	18.3	5.5	6.9	10.4	13.8
	2 groups	4.4	5.9	8.4	11.3	3.4	4.7	6.5	9.3	5.6	9.0	10.1	17.2	5.3	7.1	9.9	13.8	5.8	10.5	10.5	19.2	5.9	8.8	10.9	16.8
	3 groups	4.7	6.4	8.9	12.3	3.8	5.1	7.4	10.1	5.6	9.5	10.2	17.8	5.5	7.7	10.3	15.0	5.9	10.7	10.5	19.5	6.1	9.6	11.1	18.1

managing one or several groups of luminaires independently.

As can be observed in Tables 6 to 8, the energy saving allowed by the proposed smart controls for London is much lower than in the case of Madrid, due to the poor luminance of the average weather conditions for this particular location. Table 6 shows that shallow rooms with a sufficient window size—equal to or higher than 60%—provide a noticeable energy saving with all smart controls, despite the fact that controls B and C provide a notable increase with respect to system A for an illuminance threshold of 500 lx. As deduced from Tables 7 and 8, smart control A is almost negligible for a room depth greater than 6 m while systems B and C allow an absolute average increase of 2.8 and 6.2 kWh/m^2·year respectively, despite the fact that, as in the case of Madrid, there is not much difference between a smart system which controls two or three luminaire lines.

6. Discussion

6.1. Discussion of the findings

Considering the analysis of the proposed smart control systems according to the room geometry, smart control A is only suitable in shallow rooms with large openings, while smart control B produced a noticeable reduction in the energy consumption in electric lighting compared to control A for the specific cases of deep rooms (an increase of 41% for

Table 6

Average energy savings measured in kWh/m^2·year for rooms located in London with a 3 m depth.

Smart Control proposed	WWR	30%								60%								90%							
	Room reflectance	High				Low				High				Low				High				Low			
	Occupancy hours	Short T.		Full T.		Short T.		Full T.		Short T.		Full T.		Short T.		Full T.		Short T.		Full T.		Short T.		Full T.	
	Groups / Illuminance	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500
Smart Control A	1 group	2.9	1.7	5.1	2.8	2.2	0.0	3.9	0.0	4.5	5.3	7.5	9.6	4.0	3.7	6.9	6.8	5.4	7.3	8.7	12.6	5.1	6.1	8.5	11.2
Smart Control B	1 group	4.8	7.6	8.1	12.4	4.9	6.9	8.1	10.9	5.3	9.4	9.0	15.4	5.6	9.4	9.5	15.3	5.5	10.0	9.5	16.8	5.9	10.5	10.0	17.2
Smart Control C	1 group	5.4	9.7	9.2	16.4	5.8	10.0	9.8	16.4	5.8	10.7	9.7	18.0	6.2	11.4	10.5	19.0	5.8	11.1	9.9	19.0	6.4	11.9	10.8	20.0

Table 7

Average energy savings measured in kWh/m^2·year for rooms located in London with a 6 m depth.

Smart Control proposed	WWR	30%								60%								90%							
	Room reflectance	High				Low				High				Low				High				Low			
	Occupancy hours	Short T.		Full T.		Short T.		Full T.		Short T.		Full T.		Short T.		Full T.		Short T.		Full T.		Short T.		Full T.	
	Groups / Illuminance	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500
Smart Control A	1 group	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	3.5	0.0	0.0	0.0	0.0	0.0	2.9	1.8	5.3	3.0	1.5	0.0	2.6	0.0
	2 groups	0.9	0.0	1.6	0.0	0.4	0.0	0.6	0.0	2.7	1.6	4.9	2.9	1.5	0.7	2.7	1.2	3.7	3.6	6.4	6.3	2.8	2.2	4.9	3.9
Smart Control B	1 group	3.1	0.8	4.9	1.2	1.1	0.0	1.7	0.0	4.4	6.0	7.1	9.6	3.8	1.9	6.1	2.6	4.8	7.6	8.1	12.4	4.6	5.5	7.5	8.8
	2 groups	3.7	3.1	5.9	4.9	2.6	1.3	4.2	2.2	4.6	7.0	7.7	11.3	4.5	4.8	7.3	7.5	5.1	8.4	8.5	13.8	5.1	7.3	8.5	12.0
Smart Control C	1 group	4.5	5.7	7.1	9.4	3.9	3.4	6.5	5.5	5.2	8.4	8.5	13.9	5.1	7.6	8.6	12.5	5.5	9.4	9.1	15.8	5.6	9.2	9.4	15.2
	2 groups	4.8	7.3	8.0	12.1	4.6	6.1	7.7	10.0	5.4	9.4	9.0	15.8	5.5	9.0	9.3	15.0	5.6	10.1	9.5	17.1	5.9	10.2	9.9	17.2

rooms 6 m deep and up to 24% for deeper spaces). Control C provides better values for DA_{con} in deep rooms than systems A and B, showing an absolute increase in energy saving with respect to system A of between 66 and 84% for rooms 6 m deep and between 32 and 78% for rooms 9 m deep.

The analysis based on the room reflectance showed that dark rooms with small windows require a smart control type C, since controls A and B are not really profitable for these scenarios. Control A is not recommended in rooms with a low reflectance, except in the case of spaces with large windows—window-to-wall ratio of 90%—with an independent control of the luminaire lines.

As deduced from the results obtained, locations with predominantly overcast skies throughout the year provide a convergence of the energy savings promoted by the lighting smart controls proposed in the area near the façade, diverging in the back of the room.

Analyzing the smart controls according to user requirements, it can be observed that there is not a noticeable influence of the occupation time in the performance of the studied smart controls for mainly cloudy skies, taking into account all scenarios. The opposite occurs in locations with mainly clear skies, where in the case of smart controls B and C, full-time schedules promote an absolute increase in energy savings of up to 15% with respect to short-time, irrespective of the illuminance threshold. Thus, the illuminance threshold had a remarkable influence on the performance of the smart controls analyzed, which was almost inversely proportional to the window size.

The discussion is completed with the quantification of the energy efficiency provided by the smart controls studied, in accordance with the parameters described in the methodology. Smart control C was represented an optimal solution for deep rooms to reduce the energy consumption in locations with mainly clear sky conditions, while system B and C could be considered appropriate solutions for rooms with depths of 6 and 3 m respectively. Regardless of the location, there was no noticeable difference between a smart system which controls two or three luminaire lines, so it is advisable to promote the independent control of the lighting fixtures.

Given the aforementioned assertions, the results featured above show that there is a noticeable impact of the user behavior and of the illuminance required in the power consumption of electric lighting, especially in locations with mainly clear sky conditions, suggesting that user requirements are key to determining the suitability of the smart controls proposed based on different scenarios. This study also shows that smart systems without illuminance-meter feedback and a switching on/off control (system A) are only recommended for shallow rooms with low requirements, while dark deep rooms demand a complex dimming system managed by a common illuminance-meter placed outside, improving results when a dimming system is switched on.

Table 8
Average energy savings measured in kWh/m^2·year for rooms located in London with a 9 m depth.

Smart Control proposed	WWR	30%								60%								90%							
	Room reflectance	High				Low				High				Low				High				Low			
	Occupancy hours	Short T.		Full T.		Short T.		Full T.		Short T.		Full T.		Short T.		Full T.		Short T.		Full T.		Short T.		Full T.	
	Groups / Illuminance	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500	250	500
Smart Control A	1 group	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	1.1	0.0	0.0	0.0	0.0	0.0
	2 groups	0.6	0.0	1.0	0.0	0.3	0.0	0.5	0.0	1.1	1.0	2.0	1.8	1.0	0.5	1.8	0.8	1.9	1.7	3.2	3.1	1.4	1.4	2.4	2.4
	3 groups	0.6	0.0	1.0	0.0	0.3	0.0	0.5	0.0	1.3	1.0	2.2	1.8	1.0	0.5	1.8	0.8	2.2	1.7	3.8	3.1	1.4	1.4	2.4	2.4
Smart Control B	1 group	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	3.0	0.6	4.8	0.7	0.5	0.0	0.8	0.0	3.8	3.7	6.2	5.6	2.4	0.0	3.9	0.0
	2 groups	1.5	1.7	2.4	2.7	1.4	1.0	2.3	1.6	3.7	2.9	5.9	4.7	2.1	2.5	3.4	4.1	4.3	5.4	7.1	8.7	3.5	3.0	5.7	4.9
	3 groups	1.8	1.7	2.9	2.7	1.4	1.0	2.3	1.6	3.8	3.5	6.2	5.5	2.6	2.5	4.2	4.1	4.4	6.0	7.3	9.6	3.8	3.4	6.3	5.5
Smart Control C	1 group	2.8	2.8	4.6	4.4	1.6	1.6	2.5	2.6	4.4	5.9	7.3	9.6	3.5	3.6	5.7	5.7	4.8	7.7	8.1	12.6	4.4	5.1	7.3	8.3
	2 groups	3.6	4.7	5.9	7.6	2.8	3.8	4.6	6.3	4.8	7.2	8.0	11.9	4.3	5.8	7.2	9.6	5.1	8.7	8.6	14.4	5.0	7.2	8.4	11.9
	3 groups	3.8	5.0	6.3	8.1	3.1	4.1	5.1	6.8	4.9	7.6	8.2	12.6	4.6	6.2	7.6	10.3	5.2	8.9	8.8	14.8	5.2	7.7	8.7	12.9

6.2. *Study limitations*

The present study has the following limitations:

- It was developed through computational simulations, despite the tool and metrics were previously validated through the use of a test cell under real conditions. These simulations depend on statistical climate data of the studied location, so results can show a slight variation regarding to the real weather conditions.
- The case study analyzed consisted of a room with no urban context or remote solar obstructions.
- It was based on a small office building type, so medium and large offices, as well as other building types should be investigated (residential, educational, medical, commercial, among others).
- Calculations were performed with two locations, two occupancy schedules, two illuminance thresholds and three types of sensor-less smart control systems.
- Lighting schedules just represent occupants' behavior probabilistically, so real electric lighting energy savings can vary depending on the real human interaction.

6.3. *Future lines of research*

Given these limitations, future studies are suggested. They can be focused on increasing the number of representative locations for worldwide application results, as well as on expanding the building typologies, occupancy schedules and lighting thresholds under study. Also, given the limited number of smart control systems analyzed, it could be interesting to study additional types of smart control systems, as completely sensor-less control systems with luminous flux regulation.

Finally, the implementation of the proposed sensor-less smart control systems in real building scenarios can provide data to contrast the aforementioned results obtained by simulation.

7. Conclusions

Nowadays, the use of daylight-linked controls is not really widespread in architecture, despite its usefulness and performance in energy savings. It is therefore necessary to promote the use of lighting controls without sensors, which are easy to install and implement in buildings. Thus, this study presents the assessment of three hypotheses for smart control of electric lighting based on novel dynamic daylight metrics, quantifying the energy savings they promote according to the user's requirements.

Results of the simulations performed show that there is a noticeable impact of the user behavior and of the illuminance required in the energy consumption of electric lighting, especially in locations with mainly clear sky conditions. This finding suggests that user requirements are key to determining the suitability of the smart controls proposed based on different scenarios. This study also shows that smart controls without illuminance-meter feedback (control A) are only recommended for shallow rooms with low requirements, while dark deep rooms demand a complex dimming system managed by illuminance-meters located outside, improving results when a dimming system regulates the luminous flux of the luminaires. Thus, according to the results obtained in this study, it can be stated that the widespread implementation of these systems in building lighting design is desirable, especially for office buildings.

Declaration

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We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

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Declaration of Competing Interest

None.

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