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Dynamic Daylight Metrics for Electricity Savings in Offices: Window Size and Climate Smart Lighting Management

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Abstract: Daylight performance metrics provide a promising approach for the design and optimization of lighting strategies in buildings and their management. Smart controls for electric lighting can reduce power consumption and promote visual comfort using different control strategies, based on affordable technologies and low building impact. The aim of this research is to assess the energy efficiency of these smart controls by means of dynamic daylight performance metrics, to determine suitable solutions based on the geometry of the architecture and the weather conditions. The analysis considers different room dimensions, with variable window size and two mean surface reflectance values. DaySim 3.1 lighting software provides the simulations for the study, determining the necessary quantification of dynamic metrics to evaluate the usefulness of the proposed smart controls and their impact on energy efficiency. The validation of dynamic metrics is carried out by monitoring a mesh of illuminance-meters in test cells throughout one year. The results showed that, for most rooms more than 3.00 m deep, smart controls achieve worthwhile energy savings and a low payback period, regardless of weather conditions and for worst-case situations. It is also concluded that dimming systems provide a higher net present value and allow the use of smaller window size than other control solutions.

Keywords: daylight autonomy; window design; energy saving; smart control

1. Introduction and Objectives

1.1. State of the Art

Energy saving is one of the key variables in present-day building construction and civil engineering. In fact, lighting represents between 15% and 30% of power consumption in buildings [1–3]. Accordingly, suitable use of daylight is essential in reducing the power consumption of electric lighting [4], while the development of new technologies, such as the improvement of LED lamps or lighting smart controls, can help promote a lower impact on the environment [5].

Lighting smart controls were introduced in the early 2000s to promote energy saving in buildings. One of the first outstanding examples of their use in buildings is the New York Times Headquarters, where a lighting dimming system based on occupancy and daylight availability achieved an energy saving of close to 40% in the floor perimeters [6]. Subsequently, lighting smart controls were used in other buildings of note [7,8] with a noticeable energy saving in lighting.

Smart control strategies require the assessment of different variables: the window size is essential to determine electricity consumption [9], as are the reflectance of the room surfaces and the location of the building [10]. The illuminance controls also have a significant impact on the thermal comfort of occupants, mainly due to solar heat gain, so that algorithms should take all possible variables into account [11]. One of the most common smart controls is that of dimming systems [12,13], which adjust the electricity power of the luminaires. The dimmer can be controlled by illuminance-meters which significantly reduce the power consumption in electric lighting [14,15].

According to the latest studies [16–18], the strategies for lighting control can reduce power consumption by up to 50% when using dimming systems and close to 30% using occupant detectors. However, these technologies are not widespread, given the difficulties in installation, the limitations of the prediction algorithms, and the individual management preferences of occupants [19–21]. It is therefore important to emphasize the benefits from all these strategies, quantifying their energy efficiency and economic profitability, and avoiding an overestimation of the savings or overly optimistic analysis. Hence, the use of dynamic daylight metrics will provide a better whole-year fit. Unlike daylight static concepts, dynamic metrics allow the accurate quantification of energy savings in electric lighting, including variables not considered by static metrics, such as weather conditions, occupancy hours or illuminance thresholds required by the task being carried out [22–24].

1.2. Aim and Objectives

This research aims to assess the energy efficiency and economic profitability of lighting smart controls, determining suitable solutions according to the geometry of the architecture and the weather conditions, mainly based on the use of affordable technologies and with the lowest possible implementation cost, and with a special focus on retrofitting office buildings.

The analysis of the energy efficiency of the smart controls is deduced from the assessment of dynamic daylight performance metrics using two lighting simulation programs. The first program is Dialux 4.12, used to determine the power consumption of electric lighting to achieve an illuminance threshold, while the second, DaySim 3.1, establishes when the illuminance threshold is met by daylight alone. According to the results provided by both programs, the turn-on time of the electric lighting can be programmed, and the power consumption can be evaluated under different control proposals.

The economic profitability study is based on the analysis of the net present value, detailed in the initial investment costs of the smart controls, and the predicted minimal assured savings in the annual electricity bill—thus the use of the dynamic annual metric. This study examines the suitability of each smart control according to the room dimensions and location.

The novelty of this study is based on the analysis of daylight dynamic metrics including continuous daylight autonomy, instead of the classical approach based on static metrics—i.e., Daylight Factor—combined with the impact of the proposed solutions on economic profitability.

Energy consumption and implementation of these solutions are studied in offices. Dynamic daylight performance metrics have never been used before for quantification of the effect of dimming smart controls. This research also includes a validation of the abovementioned metrics by means of the monitoring of illuminance-meters in test cells under real conditions.

2. Description of Methodology for Calculation

2.1. Characteristics of the Room Model

2.1.1. Geometry of the Room Model

As an example of the most common office room, a virtual venue 3.00 m high with variable depth and width was used to calculate the dynamic daylight metrics and the energy saving in electric lighting. The room represents an open-plan prototypical office, where it is necessary to maintain an office-task light field suitable for the entire area. The thickness of the room walls, ceiling and floor is 0.25 m, considering a variable reflectance of the inner surfaces as well as a diffuse reflection. Thus, the light reflected is directly proportional to the cosine of the angle between the observer's line of sight and the surface normal. The different sizes of openings in the façade are defined as surface ratios. The window opening is double glazed with a visible light transmittance of 0.70 and 0.05 m thick joinery. The virtual room and calculation variables are shown in Figure 1 and Table 1.

The study points at which dynamic daylight performance metrics were analyzed were positioned on equidistant axes at a height of 0.70 m with a spacing 0.75 m wide and 0.25 m deep, as shown in Figure 1.

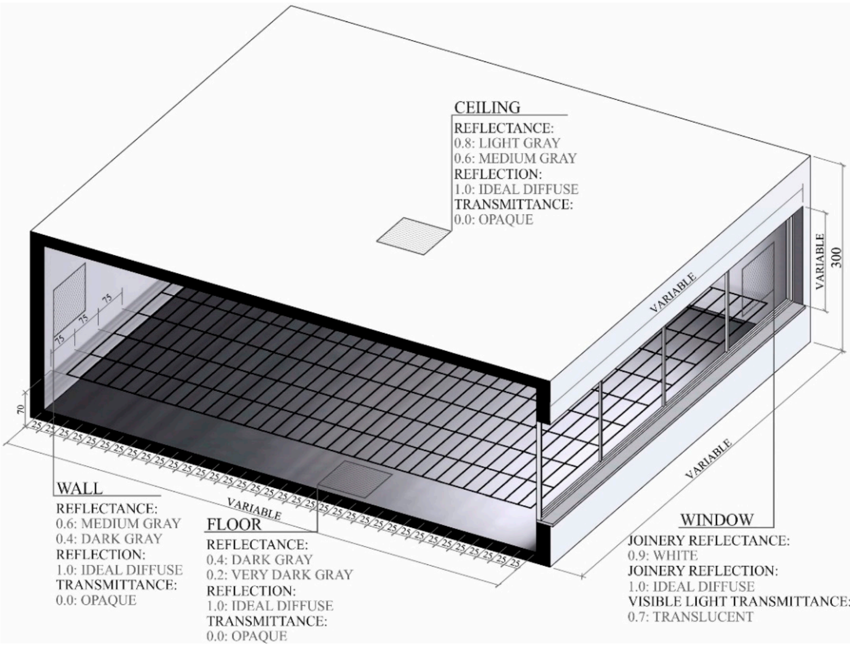


Figure 1. Calculation model.

Table 1 shows 18 room models established according to a variable depth (values of 3, 6 and 9 m), window size (window-to-façade ratio from 30 to 90%) and the reflectance of the inner surfaces.

Table 1. Room models according to variables defined.

Model	Depth	Window to Façade	Visible Light Trans-mittance	Joinery Reflectance	Ceiling Reflectance	Wall Reflectance	Floor Reflectance	Locations		
330B	3 m	30%	0.7	0.9	0.8	0.6	0.4	Stockholm (S)	London (L)	Madrid (M)
360B	3 m	60%	0.7	0.9	0.8	0.6	0.4	Stockholm (S)	London (L)	Madrid (M)
390B	3 m	90%	0.7	0.9	0.8	0.6	0.4	Stockholm (S)	London (L)	Madrid (M)
330D	3 m	30%	0.7	0.9	0.6	0.4	0.2	Stockholm (S)	London (L)	Madrid (M)
360D	3 m	60%	0.7	0.9	0.6	0.4	0.2	Stockholm (S)	London (L)	Madrid (M)
390D	3 m	90%	0.7	0.9	0.6	0.4	0.2	Stockholm (S)	London (L)	Madrid (M)
630B	6 m	30%	0.7	0.9	0.8	0.6	0.4	Stockholm (S)	London (L)	Madrid (M)
660B	6 m	60%	0.7	0.9	0.8	0.6	0.4	Stockholm (S)	London (L)	Madrid (M)
690B	6 m	90%	0.7	0.9	0.8	0.6	0.4	Stockholm (S)	London (L)	Madrid (M)
630D	6 m	30%	0.7	0.9	0.6	0.4	0.2	Stockholm (S)	London (L)	Madrid (M)
660D	6 m	60%	0.7	0.9	0.6	0.4	0.2	Stockholm (S)	London (L)	Madrid (M)
690D	6 m	90%	0.7	0.9	0.6	0.4	0.2	Stockholm (S)	London (L)	Madrid (M)
930B	9 m	30%	0.7	0.9	0.8	0.6	0.4	Stockholm (S)	London (L)	Madrid (M)
960B	9 m	60%	0.7	0.9	0.8	0.6	0.4	Stockholm (S)	London (L)	Madrid (M)
990B	9 m	90%	0.7	0.9	0.8	0.6	0.4	Stockholm (S)	London (L)	Madrid (M)
930D	9 m	30%	0.7	0.9	0.6	0.4	0.2	Stockholm (S)	London (L)	Madrid (M)
960D	9 m	60%	0.7	0.9	0.6	0.4	0.2	Stockholm (S)	London (L)	Madrid (M)
990D	9 m	90%	0.7	0.9	0.6	0.4	0.2	Stockholm (S)	London (L)	Madrid (M)

A variable width (values of 4, 8 and 12 m) was considered to assess the energy savings according to the room surface, producing a total of 54 room models. This variable barely affects the calculation results of the dynamic metrics and is therefore only used to determine the cost-effectiveness metrics used to validate the lighting smart control from an economic perspective.

2.1.2. Location of the Room Model

The room models defined were studied for three different locations—Stockholm, London and Madrid—representing a wide range of weather conditions and latitudes from 40 to 60 degrees, thus contributing to the analysis of the impact of latitude and sky luminance. Accordingly, the results obtained for Madrid could be extrapolated to the Mediterranean climate, while the conclusions for London and Stockholm could be assumed for other parts of Northern Europe.

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

The weather data for these three locations were obtained from EnergyPlus Engineering Reference [25], using direct normal and diffuse horizontal irradiances, as well as from the sky model developed by Perez et al. [26] and accepted by CIE [27]. The files selected for Stockholm and London, STOCKHOLM-ARLANDA IWEC and LONDON-GATWICK IWEC (International Weather for Energy Calculations), were created and provided by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [28]. The file selected for Madrid, MADRID SWEC (Spanish Weather for Energy Calculations), was created using data from Pérez-Lombard at the Spanish National Institute of Meteorology (AEMET) [29].

2.1.3. Orientation of the Window

All the windows in this study face north, avoiding direct sunlight since this is the worst-case scenario for indoor daylight illuminance values [30]. In office buildings facades facing north do not usually have blinds [31,32], since fundamentally their use can be limited to the control of the glare in the initial and final hours of the day, in many cases outside the working hours. The influence over the control of the annual gain of natural lighting is usually of little relevance [33]. This also allows a better comparison between locations. Despite the fact that the height of the lintel affects daylight penetration, it is not considered for this study, nor are the neighboring solar obstructions. The ground reflectance value used is 0.2, which is the default value recommended by DaySim and provided by the Radiance engine.

2.2. Lighting Design of the Room Model

The electric lighting of the virtual room consists of the use of Erco Skim downlight oval LED floodlight luminaires (Figure 2). These 37 W luminaires, with a luminous flux of 3690 lm, are arranged in parallel lines following the depth of the room: a row of luminaires is placed every 3 m deep (one, two or three rows, depending on the depth of each model), beginning at 1.5 m from the window.

This study considers an illuminance threshold of 500 lx, standard value for offices according to EN 12461-1:2012 [34]. Given that variations in the threshold cited would affect the results on the impact of energy efficiency from lighting smart controls, the illuminance value must be chosen carefully, based on use. The spacing between luminaires was calculated using Dialux 4.12, a simulation program validated by previous studies [35] and widely used in electric lighting design. In accordance with the results obtained, the separation between luminaires in each of the rows was optimized to achieve a uniformity value above 0.6 and an average illuminance of 500 lx, obtaining a spacing of 1.25 m, as can be seen in Figure 2.

To obtain a value close to the illuminance threshold, the luminaires are initially dimmed to reach 500 lx on the work plane, thus adjusting electricity consumption. The luminous flux adjustment of the lamps corresponds to 75% in those rooms with high reflectance values and to 90% for dark rooms. Defining the minimum luminous flux for each study case, the minimum energy savings promoted by lighting smart controls can be quantified.

For the sake of comparison and to keep the model as simple as possible, the base case (Case study 0) will be wired to only one command circuit. Although in this type of room it is usual to have at last two (or three) switches, it is not uncommon to find the simple all-on/off situation—mainly in older buildings. Three alternative case studies were developed (Figure 2) based on the typical control approaches for daylight saving [36]:

- Case study 1: Manual On/Off lighting control with two separate control rows: circuit 1 is for the near-façade lighting row and a second command control is for the remaining lighting rows. This system is only available for rooms 6 and 9 m deep.
- Case study 2: Common Dimming lighting control for all the luminaires of the room (single controller). The dimmer is controlled by a lux-meter which detects daylight illuminance, adjusting the power supply for the lamps.
- Case study 3: Two independent dimming-lighting-controls with two separate groups, where one circuit commands the near-façade lighting line and the other the remaining lighting rows. Systems are controlled by lux-meters which detect daylight illuminance, adjusting the power supply for the lamps. This system is only available for rooms 6 and 9 m deep.

It is worth noting that the proposed luminaires only determine the power consumption in electric lighting, following optimal location and photometric distribution. According to the results of this brief study, the electric cost, and in turn the suitability of the proposed smart controls, can be defined by their initial investment costs.

To determine the minimum energy saving of the dimming smart controls, it is assumed that occupants will not delay the activation of the switching controls to achieve the threshold of 500 lx (acting as perfect users [37]). Accordingly, the automatic response of the occupants serves to determine the tightest baseline scenario for quantifying the minimum energy savings achieved by the lighting smart controls. It is foreseeable that the savings will be higher the farther away these users are from the perfect user. It should be noted that this approach is based on daylight availability and on an ideal functioning of the control system, the response of which is actually affected by the calibration setting, the photo-sensors' characteristics and the actual daylight fluctuations, as demonstrated in previous research [38,39]. Therefore, further research is necessary in order to evaluate energy savings in a more realistic operative mode.

Moreover, as the location of the illuminance-meters affects the dimming control, these are located in the central axis of the room, 3 m from the façade (case 3) and at the back of the room near the inner wall to assure the threshold in all circumstances (worst case scenario).

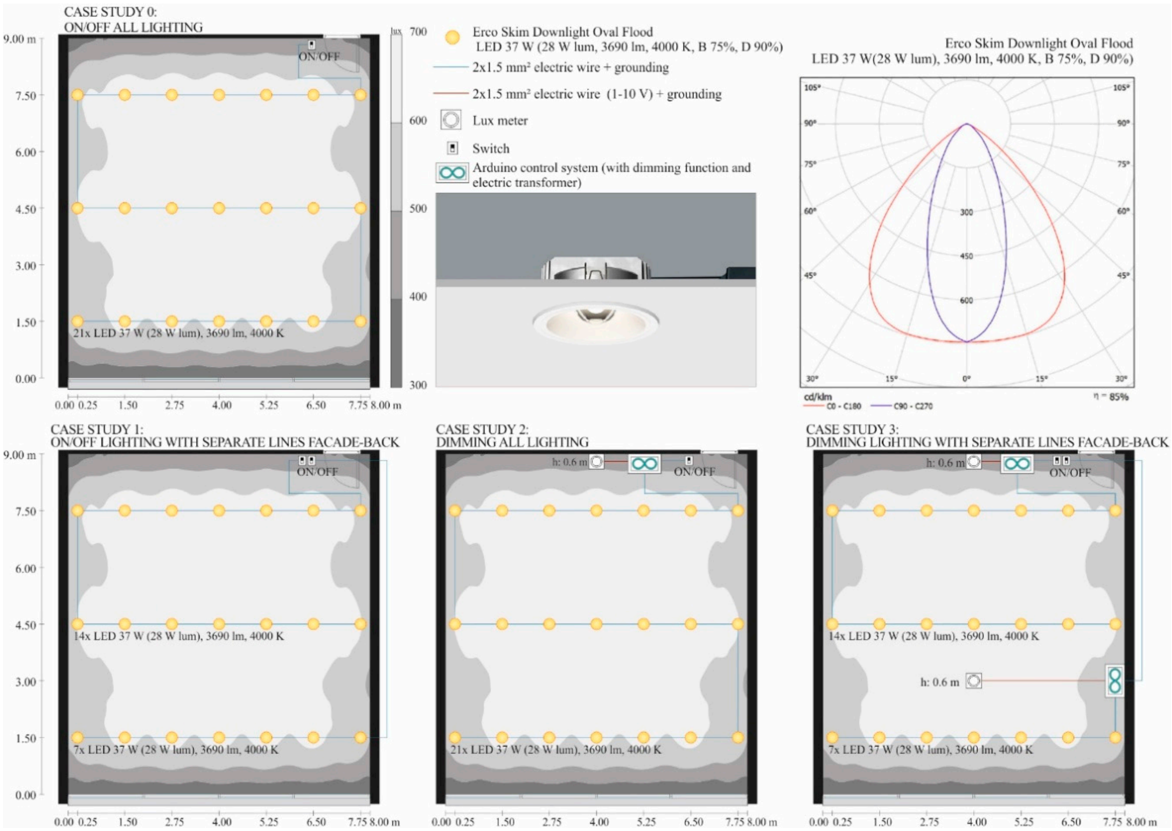


Figure 2. Lighting design of the room model and proposed smart controls.

The power consumption of other LED lamps would be very similar to those chosen for this study, obtaining a value of energy efficiency in lighting close to 1.5 W/m^2/100 lx for bright rooms and 1.7 W/m^2/100 lx for dark rooms. In the case of halogen or fluorescent lamps, the energy efficiency would be noticeably poorer, consuming more energy than the luminaires selected. Therefore, LED lamps represent the most conservative scenario for calculating the suitability of smart controls.

Since this study evaluates the initial investment costs of the proposed smart controls, Table 2 shows the economic costs of case studies 1, 2 and 3, including electric components, dimming control system, wiring and assembly costs. The total costs listed exclude the costs of the components of Case study 0, since these elements are common to all the case studies and can be considered a reference.

Table 2. Estimated initial investment costs of the proposed smart controls.

CASE 1: ON/OFF LIGHTING WITH SEPARATE ROWS FAÇADE-BACK							
MATERIAL	Cost per unit			Units	Total cost		
	Stockholm	London	Madrid		Stockholm	London	Madrid
Electric cable, single-pole, section 1.5 mm^2, crosslinked polyethylene insulation.	0.46 €/m	0.46 €/m	0.46 €/m	3.20 m	1.47 €	1.47 €	1.47 €
Single-pole switch, medium range, rated voltage 250 V, according to EN 60669.	13.90 €/U	13.90 €/U	13.90 €/U	1.00 U	13.90 €	13.90 €	13.90 €
Labor costs of electrical technician.	39.00 €/h	26.40 €/h	20.60 €/h	1.50 h	58.50 €	39.60 €	30.90 €
INITIAL INVESTMENT COSTS					**73.87 €**	**54.97 €**	**46.27 €**

Table 2. *Cont.*

CASE 2: DIMMING ALL LIGHTING							
MATERIAL	Cost per unit			Units	Total cost		
	Stockholm	London	Madrid		Stockholm	London	Madrid
Arduino Uno Rev 3 chip Atmega328 for control system, including timer, servo and connections for pulse-width modulation (PWM) control.	35.00 €/U	35.00 €/U	35.00 €/U	1.00 U	35.00 €	35.00 €	35.00 €
Electric transformer from 220/120 V to 10 V, including connections.	8.00 €/U	8.00 €/U	8.00 €/U	1.00 U	8.00 €	8.00 €	8.00 €
Mounting box of high-density polyethylene, including connections.	12.00 €/U	12.00 €/U	12.00 €/U	1.00 U	12.00 €	12.00 €	12.00 €
Lux-meter Adafruit TSL2561 Digital, spectral response according to standard photopic vision.	16.00 €/U	16.00 €/U	16.00 €/U	1.00 U	16.00 €	16.00 €	16.00 €
Labor costs of electrical technician.	39.00 €/h	26.40 €/h	20.60 €/h	2.50 h	97.50 €	66.00 €	51.50 €
INITIAL INVESTMENT COSTS					**168.50 €**	**137.00 €**	**122.50 €**
CASE 3: DIMMING LIGHTING WITH SEPARATE ROWS FAÇADE-BACK							
MATERIAL	Cost per unit			Units	Total cost		
	Stockholm	London	Madrid		Stockholm	London	Madrid
Electric cable, single-pole, section 1.5 mm^2, crosslinked polyethylene insulation.	0.46 €/m	0.46 €/m	0.46 €/m	3.20 m	1.47 €	1.47 €	1.47 €
Single-pole switch, medium range, rated voltage 250 V, according to EN 60669.	13.90 €/U	13.90 €/U	13.90 €/U	2.00 U	27.80 €	27.80 €	27.80 €
Arduino Uno Rev 3 chip Atmega328 for control system, including timer, servo and connections for PWM control.	35.00 €/U	35.00 €/U	35.00 €/U	2.00 U	70.00 €	70.00 €	70.00 €
Electric transformer from 220/120 V to 10 V, including connections.	8.00 €/U	8.00 €/U	8.00 €/U	2.00 U	16.00 €	16.00 €	16.00 €
Mounting box of high-density polyethylene, including connections.	12.00 €/U	12.00 €/U	12.00 €/U	2.00 U	24.00 €	24.00 €	24.00 €
Lux-meter Adafruit TSL2561 Digital, spectral response according to standard photopic vision.	16.00 €/U	16.00 €/U	16.00 €/U	2.00 U	32.00 €	32.00 €	32.00 €
Labor costs of electrical technician.	39.00 €/h	26.40 €/h	20.60 €/h	3.50 h	136.50 €	92.40 €	72.10 €
INITIAL INVESTMENT COSTS					**307.77 €**	**263.67 €**	**243.37 €**

2.3. Parameters of the Calculation Program

The lighting simulation program used to determine the dynamic daylight metrics and the energy saving in electric lighting is DaySim 3.1. This software is based on the Radiance engine, developed by the Building Technologies Department at the Lawrence Berkeley National Laboratory, and validated by several studies [40,41]. DaySim was designed to achieve a more accurate calculation than the initial form of Radiance, defining the current metrics according to modern sky definitions [26]. Like the Radiance engine, DaySim has been validated by several researchers [42,43] using CIE test cases [44]. Table 3 shows the calculation parameters used by this program in this study.

Table 3. Parameters of the calculation program.

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

An interval of 5 min is considered for the measuring of the illuminance values during the calculation period. The illuminance requirements and the occupancy hours are described below.

2.4. Calculation Metrics

2.4.1. Daylight Metrics and Conditions

Two dynamic metrics were assessed in the room models defined above. The first of these was daylight autonomy (DA), a concept conceived by the Association Suisse des Electriciens [45] and redefined by Reinhart et al. [46]. 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 power consumption in electric lighting. This metric can be defined as Equation (1):

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

where DA is daylight autonomy, 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 [47]. Therefore, this metric can be expressed as Equation (2):

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

where DAC is continuous daylight autonomy, 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.

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. The three locations selected for this study represent a wide range of weather conditions and latitudes from 40 to 60 degrees. As with the electric lighting design, the illuminance threshold is 500 lx, a standard value for offices according to EN 12461-1:2012 [34]. Finally, occupancy begins at 8.00 am and finishes at 5.00 pm, following the typical schedule for office rooms.

As can be deduced from the metrics described above, the assessment of daylight autonomy can determine the percentage of use of the lighting system in this time frame and thus, the power consumption in electric lighting using an On/Off control system. Moreover, the analysis of continuous daylight autonomy can ascertain not only the on-time of the electric lighting, but also the amount of light provided when it is turned on and thus, the power consumption in electric lighting when a dimming system is in place. Both metrics therefore are useful in determining the energy efficiency produced by the smart controls proposed in this study.

2.4.2. Cost-Effectiveness Metrics and Conditions

This study uses the net present value (NPV) indicator to evaluate and compare the economic profitability of the proposed lighting control hypotheses. This metric establishes the economic return on the investment for a given number of years [48], as the following expressions (Equations (3)–(5)) show:

$$NPV = -I_0 + \sum_{i=1}^{n} \frac{FB_i}{(1+D_r)^i} \tag{3}$$

$$FB_i = E_s \cdot EC \cdot AGR_E \quad (4)$$

$$AGR_E = \left(\frac{EC_{i=n}}{EC_{i=1}}\right)^{\frac{1}{n}} - 1 \quad (5)$$

where:

- I_0 is the Initial Investment cost, shown in Table 2 for each hypothesis;
- n is the Project horizon (a maximum of 10 years is considered a reasonable lifetime for LED lighting systems for office buildings (50,000 h);
- i is the Year of the study;
- FB_i is the Flow of benefits obtained in the year i (due to the savings in the annual electricity bill);
- D_r is the Discount rate (a 2.1% conservative value is assumed, as considered by energy companies [49,50]);
- E_s is Annual electric energy saving for each hypothesis, in kW·h;
- EC_i is the Annual electric energy cost for each country [51], in €/(kW·h);
- AGR_E is the Annual Growth Rate of the electric energy cost for each country.

The flow of benefits (FB_i), affected by the national price of electric energy and its fluctuations, is difficult to predict, especially when a period of 10 years is considered (NPV_{10}). This is because the Annual electric energy cost used here was that of 2016 and the Annual Growth Rate of the electric energy cost (AGR_E) was calculated from the annual electricity prices from 2005 to 2016 for each country under study, according to EUROSTAT [51]. Both EC and EC_i for each country under study are shown in Table 4:

Table 4. Annual electric cost and its annual growth rate (AGR) in Sweden, United Kingdom and Spain.

	Sweden (Stockholm)	United Kingdom (London)	Spain (Madrid)
Annual electric energy cost in 2016 (EC_{2016})	0.1894 €/(kW·h)	0.1951 €/(kW·h)	0.2185 €/(kW·h)
Annual Growth Rate 2005–2016 (AGR_E)	2.8%	7.5%	6.5%

Thus, the economic viability of the investments performed can be evaluated according to NPV value; the higher the NPV, the better the return on the lighting control system. It is also interesting to note the year in which the NPV value changes from negative to positive, as this shows when the investment starts to yield profits. This time indicator is the payback period (PP) which is assessed in this research to determine the suitability of the smart controls proposed.

3. Validation of the Calculation Program and the Dynamic Metrics

The calculation program and both dynamic metrics were validated, given that a computational simulation is not reliable until it has been compared to a real model. For this purpose, an existing test cell, located in Seville (Spain) was used as a reference [52].

3.1. Characteristics of the Test Cell for Validation Process

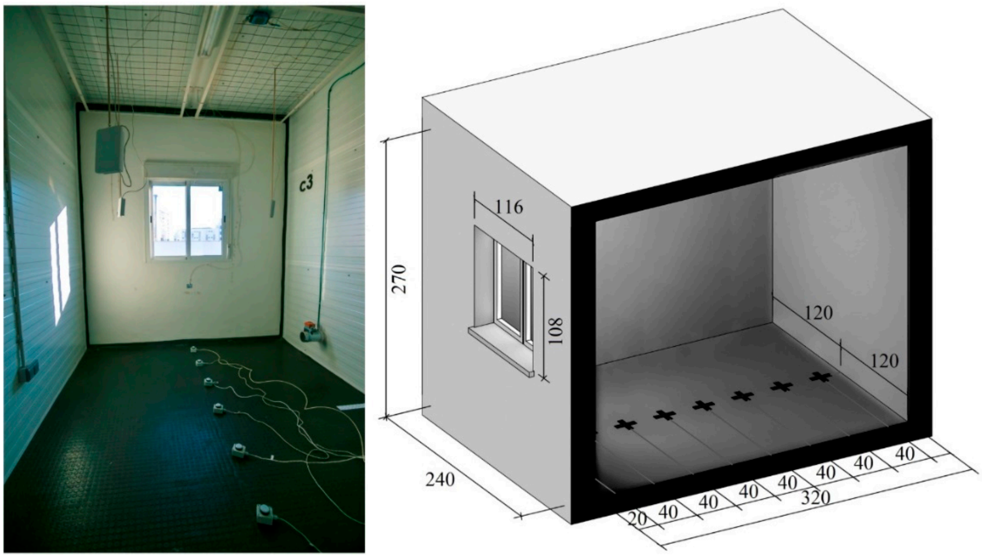
The room selected for this validation process is one of the test cells of TEP-130 research group [53], located in Seville (Spain) and facing south, in order to optimize rehabilitation solutions on façades and windows in the Mediterranean area.

The real model, which generates the predictive results for DA and DAC, is defined from the test cell characteristics, as a room 2.40 m wide by 3.20 m deep by 2.70 m high. The entire enclosure, including the floor and the roof, is built using high density sandwich panels with a combined thickness of 460 mm, colored in white and screwed to a steel frame structure. The wall facing south has a window 116 cm wide by 108 cm high, with aluminum sliding frame and double glazing (two 4 mm glass and an 8 mm air space) with a solar factor of 0.75. A conservation factor of 0.8 is considered for the glazing surface. The reflectance of the inner surfaces of the calculation model is 0.22 for the floor and 0.72 for walls and ceilings.

The illuminance values for DA and DAC indicators were measured during 2017, from 1 January to 31 December (one full year), with eight illuminance meters (range 20–2000 lx, accuracy ±3.0%) placed on the axis of symmetry of the room spaced 0.40 m apart and 0.06 m above ground level, as can be seen in Figure 3a.

3.2. Calculation Model for Validation Process

The calculation model has been defined following the geometry and characteristics of the test cell described above, as seen in Figure 3b, considering the same measures and reflectance values for the inner surfaces. As in the case of the test cell, the calculation grid of the virtual model represents the location of the illuminance meters above the floor. The calculation parameters used for this virtual model are described in Table 3.



(**a**) (**b**)

Figure 3. (**a**) Inner view of the test cell with sensor distribution, (**b**) virtual model with illuminance study points.

The weather conditions correspond to the city of Seville (Spain), located at 37.42° N and 5.40° W, with mainly clear skies. The weather data for computational computations are also obtained from SEVILLA SWEC (Spanish Weather for Energy Calculations), and a file created by Pérez-Lombard at the Spanish National Institute of Meteorology (AEMET) [29].

3.3. Calculation and Measurement Conditions of Validation Process

The calculation of daylight autonomy (DA) and continuous daylight illuminance (DAC), both for computer simulation and measurements, considered occupancy hours from 8:00 a.m. to 5:00 p.m., with no break for lunch or blind control. Given that DA and DAC depend entirely on indoor illuminance values, the illuminance threshold variable for the calculation has three values—100, 250 and 500 lux—representing the average illuminance range recommended in most common uses of architectural spaces.

3.4. Analysis of Validation Process Results

Table 5 shows the dynamic daylight metrics measured at the study points for the defined illuminance thresholds of 100, 250 and 500 lux, both from annual measurements and dynamic simulations. This table also shows the divergences between measurements and simulation, expressed in percentages.

Table 5. DA and DAC values obtained for test cell illuminance measurements and for model simulation calculations.

MEASUREMENTS																
	Daylight Autonomy (DA)								Continuous Daylight Autonomy (DAC)							
	0.2 m	0.6 m	1.0 m	1.4 m	1.8 m	2.2 m	2.6 m	3.0 m	0.2 m	0.6 m	1.0 m	1.4 m	1.8 m	2.2 m	2.6 m	3.0 m
100 lx	83%	90%	91%	91%	89%	88%	87%	86%	90%	95%	95%	95%	94%	94%	92%	92%
250 lx	68%	84%	85%	84%	80%	76%	74%	73%	81%	90%	91%	90%	89%	88%	85%	84%
500 lx	53%	72%	74%	72%	67%	63%	54%	45%	71%	84%	84%	83%	81%	79%	74%	73%
SIMULATION																
	Daylight Autonomy (DA)								Continuous Daylight Autonomy (DAC)							
	0.2 m	0.6 m	1.0 m	1.4 m	1.8 m	2.2 m	2.6 m	3.0 m	0.2 m	0.6 m	1.0 m	1.4 m	1.8 m	2.2 m	2.6 m	3.0 m
100 lx	85%	89%	89%	89%	88%	88%	87%	86%	89%	91%	91%	91%	91%	90%	90%	89%
250 lx	74%	83%	84%	83%	82%	81%	78%	77%	83%	88%	88%	88%	87%	87%	86%	85%
500 lx	56%	74%	75%	73%	69%	64%	56%	49%	74%	83%	84%	83%	81%	80%	77%	75%
DIVERGENCE MEASUREMENT-SIMULATION																
	Daylight Autonomy (DA)								Continuous Daylight Autonomy (DAC)							
	0.2 m	0.6 m	1.0 m	1.4 m	1.8 m	2.2 m	2.6 m	3.0 m	0.2 m	0.6 m	1.0 m	1.4 m	1.8 m	2.2 m	2.6 m	3.0 m
100 lx	2.0%	−1.6%	−2.7%	−2.0%	−1.5%	−0.4%	0.1%	−0.3%	−1.0%	−4.2%	−4.2%	−4.0%	−3.2%	−3.9%	−2.4%	−3.2%
250 lx	8.3%	−1.6%	−1.7%	−1.6%	2.8%	5.9%	6.1%	6.2%	2.2%	−2.5%	−2.8%	−2.4%	−2.2%	−1.2%	1.1%	0.6%
500 lx	5.8%	2.7%	2.0%	1.6%	3.5%	1.1%	3.0%	8.4%	3.8%	−0.7%	−0.3%	−0.5%	−0.1%	0.8%	3.4%	3.1%

As can be deduced from Table 5, daylight autonomy (DA) values are close to those observed in simulations, with a maximum deviation of 8.3% for 250 lux and 8.4% for 500 lux, respectively. These differences show a small and progressive divergence between measurements and simulations in relation to depth, but they can be considered acceptable due to the low values for all the illuminance thresholds.

In the case of continuous daylight autonomy (DAC) values, divergences are smaller than for DA, with a maximum deviation of 4.2% for 100 lux, but coinciding more at higher illuminance thresholds.

The bias error for both metrics is 1.9% for DA and 1.0% for DAC, with a standard deviation (95% reliability) of 6.8% and 4.9%, respectively. In both cases, these divergences are below 10% and are therefore acceptable.

From the analysis and results obtained, it is concluded that DaySim 3.1 provides an accurate calculation of dynamic daylight metrics.

4. Calculations

4.1. Quantification of Power Consumption in Stockholm

Following the methodology defined above, Figure 4 shows the sections for all room models, displaying the dynamic daylight metrics and the average power consumption measured at the central axis for each type of control system, based on the results obtained for the Stockholm location. The first column represents rooms 3.00 m deep, the second rooms 6.00 m deep and finally, the third displays rooms 9.00 m deep. Moreover, the first and second rows show the rooms with a window-to-façade ratio of 30%, the third and fourth rows rooms with a window-to-façade ratio of 60%, and the last two rows rooms with a window-to-façade ratio of 90%. Odd rows represent the bright rooms while even rows show the dark rooms. The identifier for each room, defined in Table 1, is on the upper-right side of the section.

As stated earlier, daylight autonomy can determine the average power consumption in electric lighting using an On/Off control system, given that this metric defines the percentage of the year when the threshold of 500 lx is achieved by daylight alone, establishing the turn-on time of the luminaires. Moreover, continuous daylight autonomy determines the average power consumption in electric lighting with dimming controls. Therefore, the average power consumption is shown for each luminaire row, considering On/Off and dimming controls.

Continuing with the results obtained, the average power consumption of the lighting smart controls defined in the methodology is given in Table 6, reflecting electric consumption in W/m^2 according to case studies 0 (On/Off control for all luminaires), 1 (On/Off control with two separate lines), 2 (Dimming control for all luminaires), and 3 (Dimming control with two separate lines).

It is also worth noting that the control system used in Case study 0 (an auto-switching system with one zone) affects the savings of the deepest models. For example, for a 9 m deep space, the savings decrease as the window area increases due to the fact that daylight savings are obtained in the Case study 0, and these are greater for large windows that would permit the entire room to be switched off more often.

As seen in Table 6, deeper rooms require higher power consumption, since daylight cannot reach the back of the room and the dependence on electric lighting is therefore high. This dependence is higher for dark rooms, with low reflectance of the inner surfaces, given that the reflection of daylight could contribute to an increase in illuminance and a reduction in the turn-on time of the luminaires.

Moreover, it is observed that window size has a notable effect on power consumption. Except for deep rooms with low reflectance, the largest windows (window-to-façade ratio of 90%) account for between 35% and 50% less power consumption in lighting than small windows (window-to-façade ratio of 30%). This energy saving is lower for medium windows (window-to-façade ratio of 60%) which consume between 10% and 30% less power than small windows.

Table 6. Average power consumption in W/m^2 of different lighting smart controls in Stockholm.

AVERAGE POWER CONSUMPTION (W/m^2)						
Stockholm						
Depth	**Window-to-Façade Ratio**	**Reflec-tance**	**Case Study 0**	**Case Study 1**	**Case Study 2**	**Case Study 3**
3.0 m	30%	High	3.3	3.3	2.2	2.2
3.0 m	60%	High	2.3	2.3	1.6	1.6
3.0 m	90%	High	1.9	1.9	1.4	1.4
3.0 m	30%	Low	4.9	4.9	3.1	3.1
3.0 m	60%	Low	3.4	3.4	2.2	2.2
3.0 m	90%	Low	2.8	2.8	1.9	1.9
6.0 m	30%	High	7.1	5.7	4.0	3.4
6.0 m	60%	High	4.1	3.6	2.7	2.3
6.0 m	90%	High	3.3	2.9	2.2	1.9
6.0 m	30%	Low	9.7	8.2	6.8	5.4
6.0 m	60%	Low	7.4	5.8	4.4	3.5
6.0 m	90%	Low	5.5	4.5	3.5	2.9
9.0 m	30%	High	8.1	6.9	6.3	5.2
9.0 m	60%	High	7.4	6.0	4.2	3.5
9.0 m	90%	High	5.2	4.3	3.2	2.7
9.0 m	30%	Low	9.7	8.6	8.5	7.0
9.0 m	60%	Low	9.7	7.9	7.3	5.8
9.0 m	90%	Low	9.7	7.6	6.1	4.9

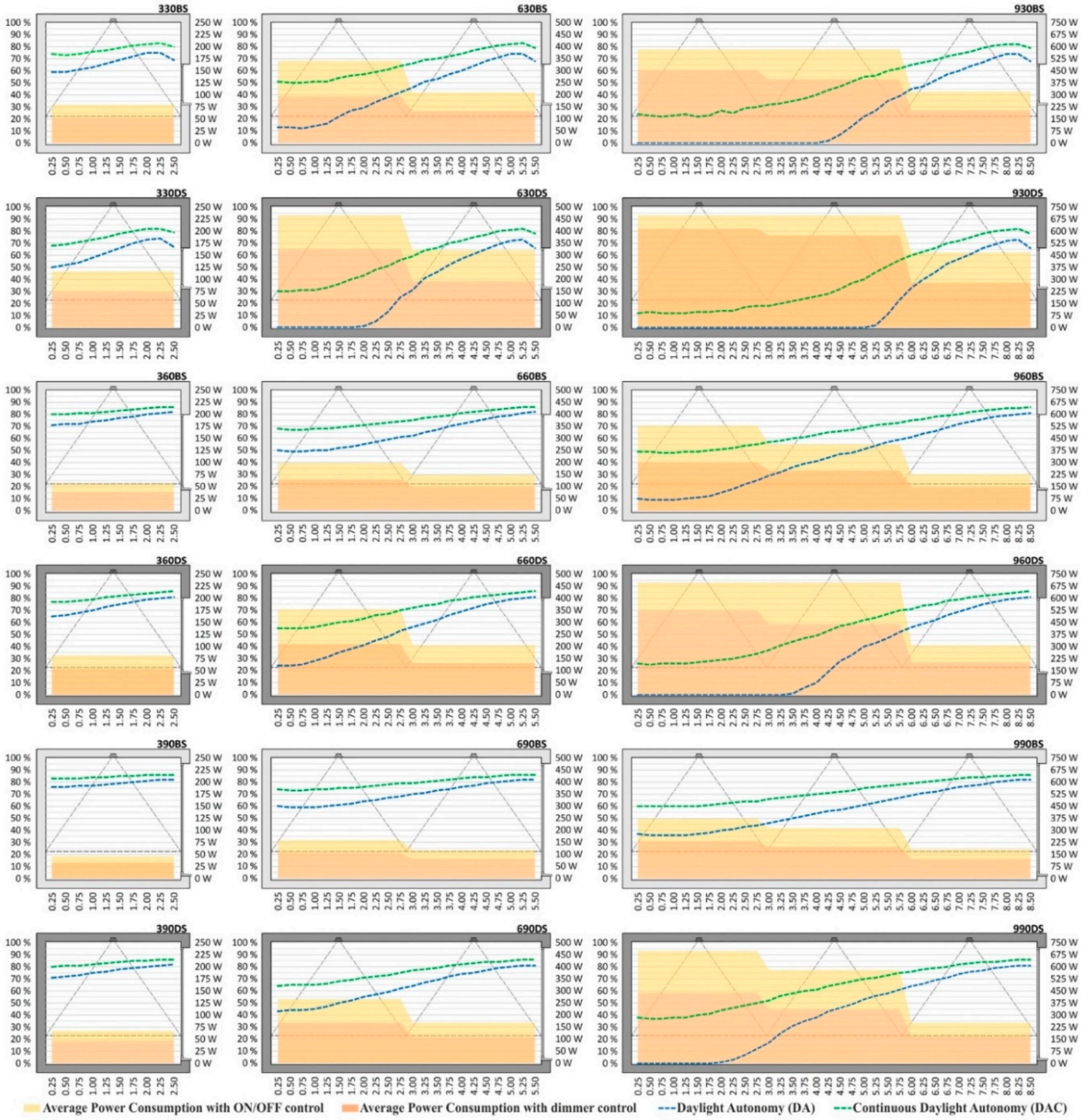


Figure 4. Dynamic daylight metrics and average power consumption according to different smart controls for room models located in Stockholm.

Finally, smart controls can reduce power consumption in electric lighting. Dimming controls specifically produce energy savings close to 30% compared to the conventional On/Off controls and the systems that control the luminaires in separate rows save up to 20% of energy. Combining both strategies, the dimming controls of separate rows of luminaires (Case study 3) can save between 35% and 55% compared to the typical On/Off control (Case study 0).

Based on the results in Figure 4 and Table 6, the annual energy saving is summarized in Table 7, depending on the room dimensions, window size, surface reflectances and smart controls proposed. The annual energy saving is obtained by comparing the average power consumption of case studies 1 (On/Off control with two separate rows), 2 (Dimming control for all luminaires), and 3 (Dimming control with two separate rows) to the typical On/Off control, defined as Case study 0.

Table 7. Annual energy saving in kWh of different lighting smart controls in Stockholm.

ANNUAL ENERGY SAVING (kWh)											
Stockholm											
		Width	**12.0 m**	**8.0 m**	**4.0 m**	**12.0 m**	**8.0 m**	**4.0 m**	**12.0 m**	**8.0 m**	**4.0 m**
Depth	**Window-to-Façade Ratio**	**Reflec-tance**	**Case Study 3: Dimming Control with Two Separate Rows**			**Case Study 2: Dimming Control for All Luminaires**			**Case Study 1: On/Off Control with Two Separate Rows**		
3.0 m	30%	High	-	-	-	106	71	35	-	-	-
3.0 m	60%	High	-	-	-	68	45	23	-	-	-
3.0 m	90%	High	-	-	-	53	35	18	-	-	-
3.0 m	30%	Low	-	-	-	164	109	55	-	-	-
3.0 m	60%	Low	-	-	-	109	73	36	-	-	-
3.0 m	90%	Low	-	-	-	82	55	27	-	-	-
6.0 m	30%	High	697	465	232	576	384	192	258	172	86
6.0 m	60%	High	333	222	111	273	182	91	98	66	33
6.0 m	90%	High	258	172	86	212	141	71	83	56	28
6.0 m	30%	Low	809	539	270	545	364	182	282	188	94
6.0 m	60%	Low	718	479	239	564	376	188	291	194	97
6.0 m	90%	Low	500	333	167	382	255	127	191	127	64
9.0 m	30%	High	826	551	275	500	333	167	341	227	114
9.0 m	60%	High	1091	727	364	886	591	295	394	263	131
9.0 m	90%	High	689	460	230	545	364	182	250	167	83
9.0 m	30%	Low	764	509	255	327	218	109	300	200	100
9.0 m	60%	Low	1100	733	367	682	455	227	509	339	170
9.0 m	90%	Low	1364	909	455	1009	673	336	582	388	194

As Table 7 shows, energy saving is higher for cases with small windows which depend more on electric lighting. This rule does not apply to deep rooms, because the conventional On/Off control (Case study 0) is almost always on regardless of window size, and the smart controls save more energy in this case, even more so with large windows.

Moreover, it is worth noting that the use of smaller windows, which may consume more energy in electric lighting, can make up for this weak point using smart controls. For example, a room with a medium window (window-to-façade ratio of 60%) can produce higher energy savings than a room with a larger window if a dimming control with two separate rows (Case study 3) is used.

4.2. *Quantification of Power Consumption in London*

Figure 5 shows the cross sections for all room models for the London location, together with the dynamic daylight metrics and the average power consumption at the central axis. This figure has a similar structure to the previous one, defining the depth of the room in the columns and the window size and reflectance of the surfaces in rows. As in the calculation above, the identifier for each room, defined in Table 1, is on the upper-right side of each section.

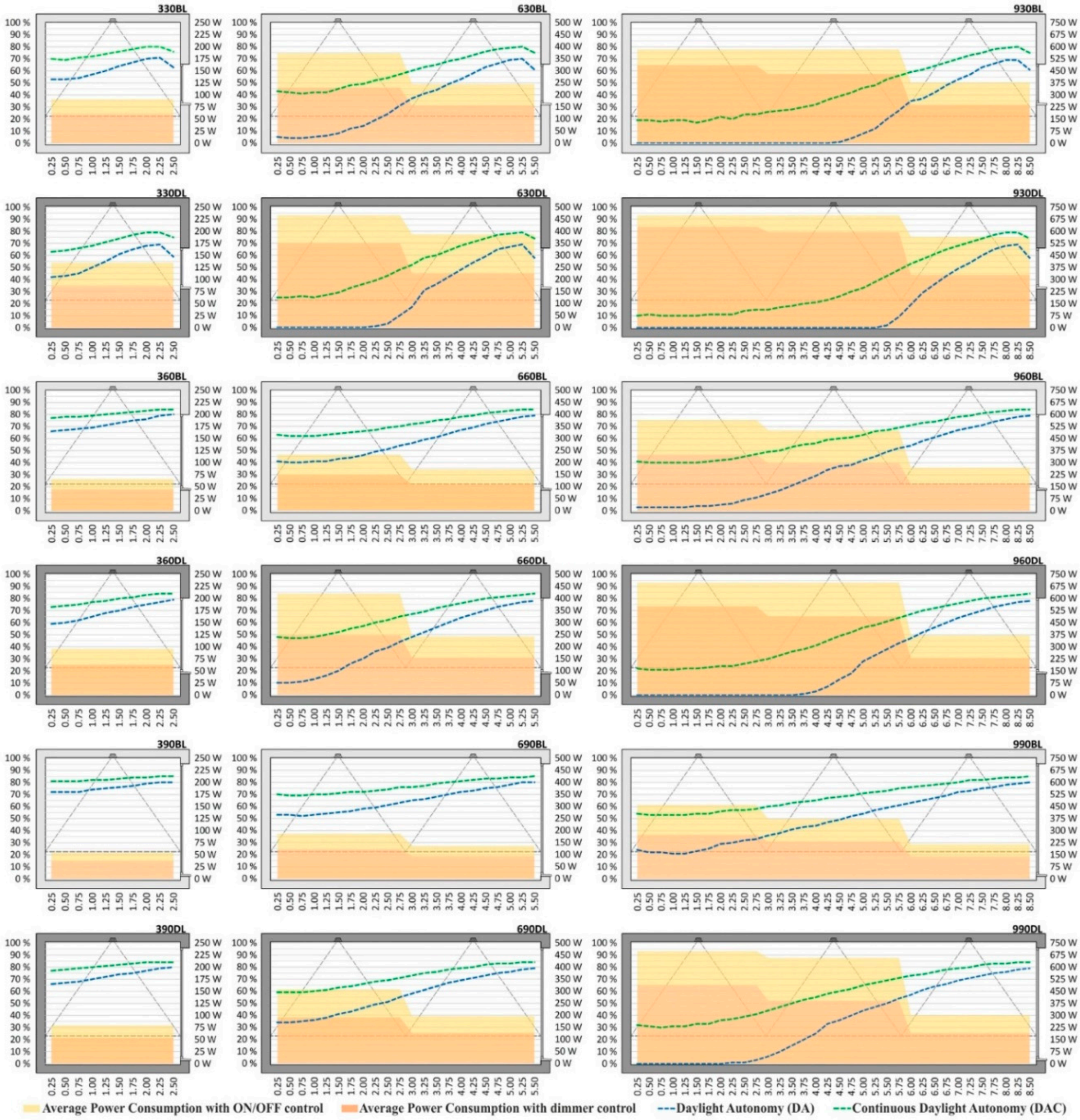


Figure 5. Daylight dynamic metrics and average power consumption according to different smart controls for room models located in London.

As in the previous calculation, the average power consumption of lighting smart controls are found in Table 8, which shows the electric consumption in W/m^2 for each Case study.

Table 8. Average power consumption in W/m^2 of different lighting smart controls in London.

AVERAGE POWER CONSUMPTION (W/m^2)						
London						
Depth	**Window-to-Façade Ratio**	**Reflec-tance**	**Case Study 0**	**Case Study 1**	**Case Study 2**	**Case Study 3**
3.0 m	30%	High	3.8	3.8	2.5	2.5
3.0 m	60%	High	2.8	2.8	1.9	1.9
3.0 m	90%	High	2.3	2.3	1.5	1.5
3.0 m	30%	Low	5.6	5.6	3.6	3.6
3.0 m	60%	Low	4.0	4.0	2.6	2.6
3.0 m	90%	Low	3.3	3.3	2.2	2.2
6.0 m	30%	High	7.8	6.4	4.8	4.0
6.0 m	60%	High	4.9	4.2	3.1	2.7
6.0 m	90%	High	3.9	3.4	2.5	2.2
6.0 m	30%	Low	9.7	8.9	7.3	6.0
6.0 m	60%	Low	8.7	6.9	5.1	4.2
6.0 m	90%	Low	6.4	5.2	4.0	3.3
9.0 m	30%	High	8.1	7.1	6.7	5.6
9.0 m	60%	High	7.9	6.5	4.9	4.0
9.0 m	90%	High	6.4	5.3	3.8	3.2
9.0 m	30%	Low	9.7	9.1	8.7	7.3
9.0 m	60%	Low	9.7	8.2	7.7	6.2
9.0 m	90%	Low	9.7	7.9	6.8	5.4

As seen in Table 8 and deduced from the previous trial, the deep rooms need higher power consumption for electric lighting, since daylight cannot reach the back of the room. In this case, window size is decisive in reducing the power consumption, given that large windows consume between 20% and 50% less power than small windows.

Comparison of Tables 6 and 8 shows that the room model in the London location requires approximately 13% more energy than the Stockholm location. The difference between the locations only tends to converge for deep rooms, given that the daylight is not sufficient to light the entire venue in either case. It can therefore be deduced that weather conditions are more significant than latitude in the calculation of power consumption in electric lighting.

As in the previous case, smart controls notably reduce power consumption in electric lighting. The dimming controls save nearly 30% of energy compared to the typical On/Off controls, while the dimming controls with separate rows reduce power consumption by up to 50%.

Following on from Figure 5 and Table 8, Table 9 shows the annual energy saving, based on proposed room dimensions, window size, surface reflectances and smart controls. As before, the annual energy saving is calculated comparing the average power consumption of the smart controls to that of the conventional On/Off control.

Table 9. Annual energy saving in kWh of different lighting smart controls in London.

ANNUAL ENERGY SAVING (kWh)											
London											
		Width	**12.0 m**	**8.0 m**	**4.0 m**	**12.0 m**	**8.0 m**	**4.0 m**	**12.0 m**	**8.0 m**	**4.0 m**
Depth	**Window-to-Façade Ratio**	**Reflec-tance**	**Case Study 3: Dimming Control with Two Separate Rows**			**Case Study 2: Dimming Control for All Luminaires**			**Case Study 1: On/Off Control with Two Separate Rows**		
3.0 m	30%	High	-	-	-	121	81	40	-	-	-
3.0 m	60%	High	-	-	-	83	56	28	-	-	-
3.0 m	90%	High	-	-	-	68	45	23	-	-	-
3.0 m	30%	Low	-	-	-	191	127	64	-	-	-
3.0 m	60%	Low	-	-	-	127	85	42	-	-	-
3.0 m	90%	Low	-	-	-	100	67	33	-	-	-
6.0 m	30%	High	705	470	235	561	374	187	250	167	83
6.0 m	60%	High	409	273	136	333	222	111	121	81	40
6.0 m	90%	High	311	207	104	258	172	86	98	66	33
6.0 m	30%	Low	700	467	233	455	303	152	155	103	52
6.0 m	60%	Low	855	570	285	673	448	224	345	230	115
6.0 m	90%	Low	582	388	194	455	303	152	218	145	73
9.0 m	30%	High	705	470	235	386	258	129	265	177	88
9.0 m	60%	High	1076	717	359	841	561	280	386	258	129
9.0 m	90%	High	902	601	301	727	485	242	318	212	106
9.0 m	30%	Low	664	442	221	273	182	91	173	115	58
9.0 m	60%	Low	991	661	330	573	382	191	427	285	142
9.0 m	90%	Low	1209	806	403	818	545	273	518	345	173

As seen in Table 9, converging with the results shown for the Stockholm location, the energy saving is higher for rooms with small windows, except in the case of deep rooms. As above, it can be concluded that a room with a small window can compensate for power consumption using a dimming control with two separate rows (Case study 3), compared to other rooms with larger windows and less efficient smart controls (case studies 1 and 2).

As deduced from Figure 5 and Table 6 above, owing to worse weather conditions the power consumption for London is higher than that for Stockholm. However, comparison of Tables 7 and 9 shows that the energy saving in London is higher for narrow rooms. In fact, rooms 3.00 m deep increase energy saving by almost 20% for dimming controls compared to Stockholm. The opposite occurs in the case of deep rooms, as the energy savings of dimming controls are slightly higher in Stockholm.

4.3. Quantification of Power Consumption in Madrid

As above, Figure 6 describes the cross sections for all room models for the Madrid location, defining the dynamic daylight metrics and the average power consumption at the central axis. This figure follows the same structure as the previous ones. The identifier for each room, defined in Table 1, is on the upper-right side of each section.

Table 10 shows the average power consumption of lighting smart controls in W/m^2, based on the case studies.

In line with previous results Table 10 shows that the power consumption in electric lighting for deep rooms with conventional On/Off controls is similar for all locations, irrespective of weather conditions and the reflectance of the inner surfaces. This is because daylight cannot reach the illuminance threshold in the entire room. Therefore, the use of smart controls is even more advantageous in locations with clear skies.

Following the analysis and results of Table 10, except for deep rooms with a low reflectance, large windows (window-to-façade ratio of 90%) consume between 40% and 75% less in lighting than small windows (window-to-façade ratio of 30%). It can be deduced that the impact of a large window on energy efficiency is higher for sites with better weather conditions, and a higher sky luminance.

Table 10. Average power consumption in W/m^2 of different lighting smart controls in Madrid.

AVERAGE POWER CONSUMPTION (W/m^2)						
Madrid						
Depth	Window-to-Façade Ratio	Reflec-tance	Case Study 0	Case Study 1	Case Study 2	Case Study 3
3.0 m	30%	High	1.7	1.7	1.1	1.1
3.0 m	60%	High	1.1	1.1	0.7	0.7
3.0 m	90%	High	0.9	0.9	0.6	0.6
3.0 m	30%	Low	3.0	3.0	1.7	1.7
3.0 m	60%	Low	1.7	1.7	1.1	1.1
3.0 m	90%	Low	1.3	1.3	1.0	1.0
6.0 m	30%	High	6.1	4.5	2.7	2.1
6.0 m	60%	High	2.3	1.9	1.3	1.1
6.0 m	90%	High	1.6	1.4	1.0	0.9
6.0 m	30%	Low	9.7	7.7	5.7	4.1
6.0 m	60%	Low	6.1	4.3	2.7	2.0
6.0 m	90%	Low	3.6	2.7	1.8	1.5
9.0 m	30%	High	8.1	6.4	5.7	4.3
9.0 m	60%	High	6.4	4.8	2.8	2.2
9.0 m	90%	High	3.8	2.9	1.9	1.5
9.0 m	30%	Low	9.7	8.4	8.2	6.2
9.0 m	60%	Low	9.7	7.3	6.3	4.7
9.0 m	90%	Low	9.7	7.1	4.8	3.6

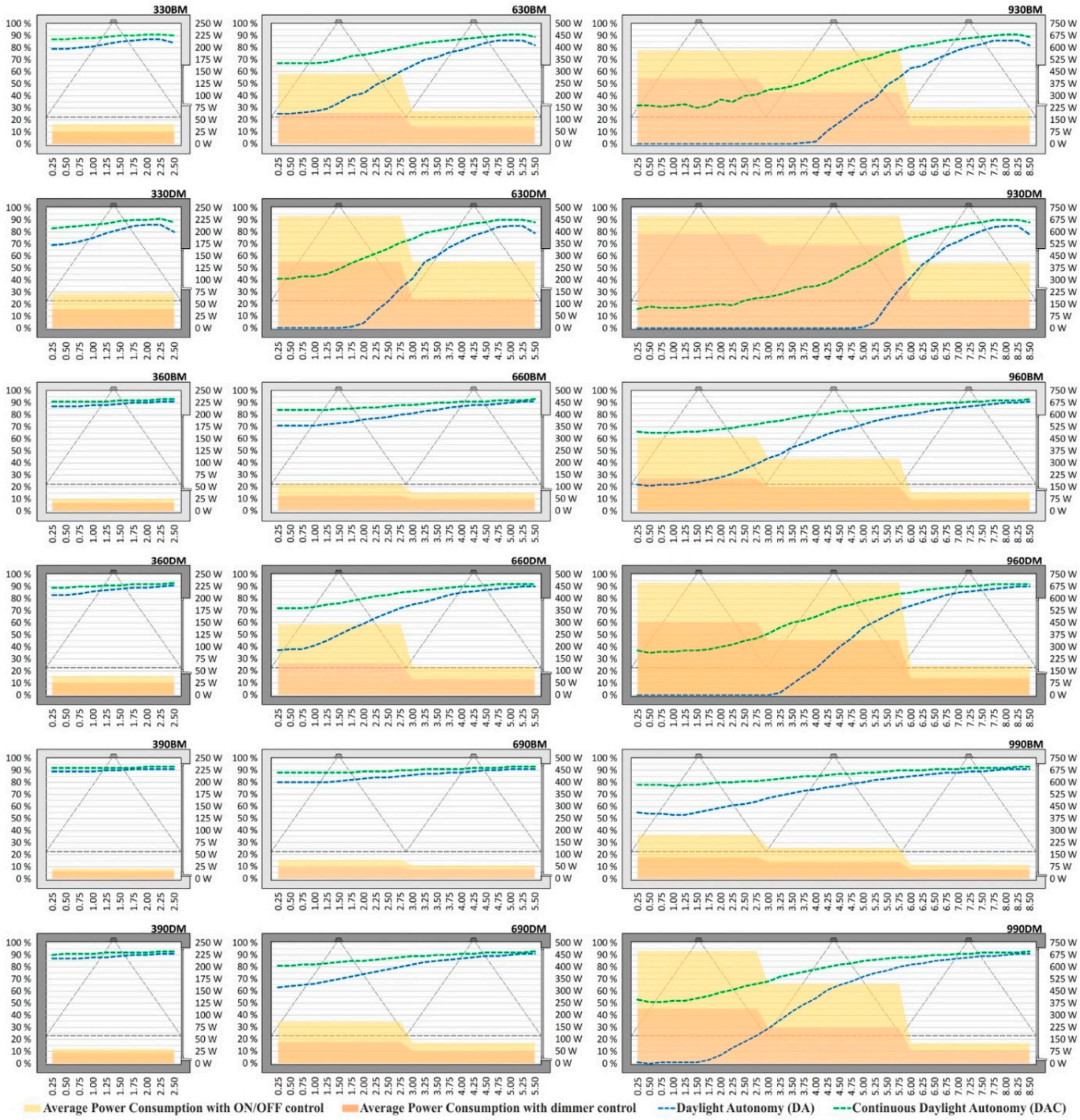


Figure 6. Dynamic daylight performance metrics and average power consumption according to different smart controls for room models located in Madrid.

From the above, the room model in the Madrid location consumes almost 40% less power consumption than London and almost 35% less than Stockholm.

As seen above, the smart controls are decisive in controlling power consumption in electric lighting. Extending this statement to all the locations studied, the dimming controls (Case study 2) produce an energy saving of close to 30% compared to the typical On/Off controls, while the dimming controls with separate rows (Case study 3) reduce power consumption by up to 55%. Moreover, the On/Off lighting control with separate rows (Case study 1) can reduce power consumption by up to 20% compared to the On/Off system with one row for all luminaires.

In accordance with the results of Figure 6 and Table 10, the annual energy saving is determined in Table 11, based on the proposed room dimensions, window size, surface reflectances and smart controls. As above, the annual energy saving is calculated by comparing the average power consumption of the smart controls proposed to that produced by the conventional On/Off control.

As seen in Table 11 and previously, energy saving is higher for rooms with small windows, due to the high dependence on electric lighting. Deep rooms are an exception, as the conventional On/Off control is almost always on, regardless of window size. As in the cases above, a room with a small window can save more energy than other rooms with larger windows and less efficient smart controls by using dimming control with two separate rows.

Table 11. Annual energy saving in kWh of different lighting smart controls in Madrid.

ANNUAL ENERGY SAVING (kWh)											
Madrid											
		Width	12.0 m	8.0 m	4.0 m	12.0 m	8.0 m	4.0 m	12.0 m	8.0 m	4.0 m
Depth	Window-to-Façade Ratio	Reflec-tance	Case Study 3: Dimming Control with Two Separate Rows			Case Study 2: Dimming Control for All Luminaires			Case Study 1: On/Off Control with Two Separate Rows		
3.0 m	30%	High	-	-	-	61	40	20	-	-	-
3.0 m	60%	High	-	-	-	30	20	10	-	-	-
3.0 m	90%	High	-	-	-	23	15	8	-	-	-
3.0 m	30%	Low	-	-	-	127	85	42	-	-	-
3.0 m	60%	Low	-	-	-	55	36	18	-	-	-
3.0 m	90%	Low	-	-	-	27	18	9	-	-	-
6.0 m	30%	High	750	500	250	636	424	212	303	202	101
6.0 m	60%	High	227	152	76	197	131	66	76	51	25
6.0 m	90%	High	136	91	45	121	81	40	45	30	15
6.0 m	30%	Low	1045	697	348	745	497	248	373	248	124
6.0 m	60%	Low	764	509	255	636	424	212	345	230	115
6.0 m	90%	Low	400	267	133	327	218	109	173	115	58
9.0 m	30%	High	1068	712	356	682	455	227	477	318	159
9.0 m	60%	High	1174	783	391	1000	667	333	447	298	149
9.0 m	90%	High	644	429	215	545	364	182	242	162	81
9.0 m	30%	Low	973	648	324	436	291	145	382	255	127
9.0 m	60%	Low	1409	939	470	955	636	318	673	448	224
9.0 m	90%	Low	1727	1152	576	1391	927	464	745	497	248

A comparison of Tables 7, 9 and 11 shows that the energy saving in Madrid is noticeably lower than in London or Stockholm for rooms 3.00 m deep, achieving an average of 40% less, based on the selection of a base case (system 0) that is auto-switched by users. However, the deeper rooms in Madrid can save up to 40% energy compared to other sites. In conclusion, considering rooms between 6.00 m and 9.00 m deep, the greater the sky luminance, the higher the energy savings with lighting smart controls. Moreover, the opposite of this statement is true for rooms 6.00 m deep or less.

5. Analysis of Payback Period and Net Present Value

5.1. Cost Effectiveness in Stockholm

According to Section 2, the profitability of the different hypotheses for lighting control in Stockholm are compared using the payback period (PP) and the 10-year-investment NPV (NPV10).

Table 12 shows that adequate PPs are achieved for the three control systems in rooms 6.00 m deep or more (PP average value of 4.5 years), but these are not recommended for rooms 3.00 m deep (PP average value of 18.6 years). When width is analyzed in rooms 6.00 m deep or more, it is worth noting that PP decreases for rooms 8.00 m wide or more, (PP average value of 3.3 years). Increasing the technical complexity of the control system extends the payback period, as the initial investment costs correlate to complexity (PP average value of 2.9, 3.0 and 3.9 years for cases 1, 2 and 3 respectively).

Table 12. Payback period according to different lighting smart controls in Stockholm.

PAYBACK PERIOD											
Stockholm											
		Width	**12.0 m**	**8.0 m**	**4.0 m**	**12.0 m**	**8.0 m**	**4.0 m**	**12.0 m**	**8.0 m**	**4.0 m**
Depth	**Window-to-Façade Ratio**	**Reflec-tance**	**Case Study 3: Dimming Control with Two Separate Rows**			**Case Study 2: Dimming Control for all Luminaires**			**Case Study 1: On/Off Control with Two Separate Rows**		
3.0 m	30%	High	-	-	-	9 years	13 years	24 years	-	-	-
3.0 m	60%	High	-	-	-	13 years	19 years	36 years	-	-	-
3.0 m	90%	High	-	-	-	17 years	24 years	45 years	-	-	-
3.0 m	30%	Low	-	-	-	6 years	9 years	16 years	-	-	-
3.0 m	60%	Low	-	-	-	9 years	13 years	24 years	-	-	-
3.0 m	90%	Low	-	-	-	11 years	16 years	31 years	-	-	-
6.0 m	30%	High	3 years	4 years	7 years	2 years	3 years	5 years	2 years	3 years	5 years
6.0 m	60%	High	5 years	8 years	15 years	4 years	5 years	10 years	5 years	6 years	12 years
6.0 m	90%	High	7 years	10 years	19 years	5 years	7 years	13 years	5 years	8 years	14 years
6.0 m	30%	Low	3 years	4 years	7 years	2 years	3 years	5 years	2 years	3 years	5 years
6.0 m	60%	Low	3 years	4 years	7 years	2 years	3 years	5 years	2 years	3 years	5 years
6.0 m	90%	Low	4 years	5 years	10 years	3 years	4 years	7 years	3 years	4 years	7 years
9.0 m	30%	High	3 years	3 years	6 years	2 years	3 years	6 years	2 years	2 years	4 years
9.0 m	60%	High	2 years	3 years	5 years	2 years	2 years	4 years	2 years	2 years	4 years
9.0 m	90%	High	3 years	4 years	8 years	2 years	3 years	5 years	2 years	3 years	5 years
9.0 m	30%	Low	3 years	4 years	7 years	3 years	5 years	9 years	2 years	2 years	4 years
9.0 m	60%	Low	2 years	3 years	5 years	2 years	2 years	4 years	1 years	2 years	3 years
9.0 m	90%	Low	2 years	2 years	4 years	1 years	2 years	3 years	1 years	2 years	3 years

Table 13 shows that adequate NPV10 is obtained in the same way for rooms 6.00 m deep or more (average NPV10 of 497.90 € compared to −44.83 € in the case of 3.00 m deep), and especially for rooms 8.00 m wide or more (average NPV10 of 668.22 €). However, unlike the payback period, the NPV10 shows that the more complex the control system in larger rooms, the greater the economic benefits obtained after 10 years. Using a smart control instead of an On/Off manual control with two separate rows (case 1) ultimately provides an economic saving of 73% in the case of dimming control for all luminaires (case 2), and 126% for smart control with two separate rows (case 3), as energy savings are greater in the long term despite their higher initial investment costs.

As with power consumption, the profitability of the smart systems is higher for rooms at least 8.00 m wide and small windows, except in the case of deep rooms with dark surfaces. For example, all NPV10 values of Case study 3 with small windows (window-to-façade ratio of 30%) are equal to or greater than the NPV10 values of Case study 1 with the largest windows (window-to-façade ratio of 90%).

Table 13. Net present value in 10 years according to different lighting smart controls in Stockholm.

NET PRESENT VALUE IN 10 YEARS											
Stockholm											
		Width	**12.0 m**	**8.0 m**	**4.0 m**	**12.0 m**	**8.0 m**	**4.0 m**	**12.0 m**	**8.0 m**	**4.0 m**
Depth	**Window-to-Façade Ratio**	**Reflec-tance**	**Case Study 3: Dimming Control with Two Separate Rows**			**Case Study 2: Dimming Control for All Luminaires**			**Case Study 1: On/Off Control with Two Separate Rows**		
3.0 m	30%	High	-	-	-	34 €	−33 €	−101 €	-	-	-
3.0 m	60%	High	-	-	-	−38 €	−82 €	−125 €	-	-	-
3.0 m	90%	High	-	-	-	−67 €	−101 €	−135 €	-	-	-
3.0 m	30%	Low	-	-	-	145 €	40 €	−64 €	-	-	-
3.0 m	60%	Low	-	-	-	40 €	−29 €	−99 €	-	-	-
3.0 m	90%	Low	-	-	-	−12 €	−64 €	−116 €	-	-	-
6.0 m	30%	High	1026 €	581 €	137 €	933 €	566 €	199 €	419 €	255 €	90 €
6.0 m	60%	High	330 €	117 €	−95 €	353 €	179 €	5 €	115 €	52 €	−11 €
6.0 m	90%	High	185 €	21 €	−143 €	237 €	102 €	−33 €	86 €	32 €	−21 €
6.0 m	30%	Low	1240 €	724 €	208 €	875 €	527 €	179 €	465 €	286 €	106 €
6.0 m	60%	Low	1066 €	608 €	150 €	910 €	550 €	191 €	483 €	297 €	112 €
6.0 m	90%	Low	649 €	330 €	11 €	562 €	319 €	75 €	291 €	170 €	48 €
9.0 m	30%	High	1272 €	746 €	219 €	788 €	469 €	150 €	578 €	361 €	144 €
9.0 m	60%	High	1780 €	1084 €	388 €	1527 €	962 €	397 €	680 €	429 €	177 €
9.0 m	90%	High	1011 €	572 €	132 €	875 €	527 €	179 €	404 €	245 €	86 €
9.0 m	30%	Low	1153 €	666 €	179 €	458 €	249 €	40 €	500 €	309 €	117 €
9.0 m	60%	Low	1797 €	1095 €	394 €	1136 €	701 €	266 €	900 €	576 €	251 €
9.0 m	90%	Low	2301 €	1432 €	562 €	1762 €	1119 €	475 €	1039 €	668 €	297 €

5.2. Cost Effectiveness in London

The PP for the three control systems for the London room model is shown in Table 14. Considering the sky conditions and as shown in Table 4, in general PP is 33.5% lower for all the London hypotheses since both the annual electric energy cost in 2016 (EC2016) and the annual growth rate (AGRE) in the United Kingdom are higher than in Sweden. Nevertheless, the use of these three system controls is still advantageous to rooms 6.00 m deep or more (PP average value of 3.3 years compared to 10.1 years in the case of 3.00 m deep), except when they are 12.00 m wide or more (PP average value of 6.7 years). As in the case of Stockholm, the wider the deep rooms, the lower the PP for all the control systems (PP average value of 2.5 years in rooms 8.00 m wide or more), resulting in an average PP decrease of 23.8% compared to Stockholm.

As seen in Stockholm, Table 15 shows that adequate NPV10 is related to depths equal to or greater than 6.00 m (average NPV10 of 693.32 €, a 39.3% increase compared to Stockholm), especially for widths of 8.00 m or more (average NPV10 of 904.60 €, an increase of 35.4%). In the same way, the most complex control systems save most after 10 years, as the average economic saving for smart control systems compared to case 1 is 88% for case 2 and 156% for case 3. These economic results are more significant than the Stockholm ones (a NPV10 increase of 24.3%, 34.8% and 40.7% in the three cases) due both to the higher electric energy cost in the United Kingdom and the higher annual energy saving of lighting control systems in London.

Table 14. Payback period according to different lighting smart controls in London.

PAYBACK PERIOD											
London											
		Width	12.0 m	8.0 m	4.0 m	12.0 m	8.0 m	4.0 m	12.0 m	8.0 m	4.0 m
Depth	Window-to-Façade Ratio	Reflec-tance	Case Study 3: Dimming Control with Two Separate Rows			Case Study 2: Dimming Control for All Luminaires			Case Study 1: On/Off Control with Two Separate Rows		
3.0 m	30%	High	-	-	-	6 years	8 years	13 years	-	-	-
3.0 m	60%	High	-	-	-	8 years	11 years	17 years	-	-	-
3.0 m	90%	High	-	-	-	9 years	12 years	20 years	-	-	-
3.0 m	30%	Low	-	-	-	4 years	6 years	10 years	-	-	-
3.0 m	60%	Low	-	-	-	6 years	8 years	13 years	-	-	-
3.0 m	90%	Low	-	-	-	7 years	9 years	15 years	-	-	-
6.0 m	30%	High	2 years	3 years	6 years	2 years	2 years	4 years	2 years	2 years	4 years
6.0 m	60%	High	4 years	5 years	9 years	3 years	4 years	6 years	3 years	4 years	7 years
6.0 m	90%	High	5 years	6 years	11 years	3 years	4 years	8 years	3 years	5 years	8 years
6.0 m	30%	Low	2 years	3 years	6 years	2 years	3 years	5 years	2 years	3 years	6 years
6.0 m	60%	Low	2 years	3 years	5 years	2 years	2 years	4 years	1 years	2 years	3 years
6.0 m	90%	Low	3 years	4 years	7 years	2 years	3 years	5 years	2 years	2 years	4 years
9.0 m	30%	High	2 years	3 years	6 years	2 years	3 years	6 years	2 years	2 years	4 years
9.0 m	60%	High	2 years	2 years	4 years	1 years	2 years	3 years	1 years	2 years	3 years
9.0 m	90%	High	2 years	3 years	5 years	1 years	2 years	3 years	1 years	2 years	3 years
9.0 m	30%	Low	3 years	3 years	6 years	3 years	4 years	7 years	2 years	3 years	5 years
9.0 m	60%	Low	2 years	3 years	4 years	2 years	2 years	4 years	1 years	2 years	2 years
9.0 m	90%	Low	2 years	2 years	4 years	1 years	2 years	3 years	1 years	1 years	2 years

In line with the Stockholm results, the lighting system of a room with a small window can be more economical using a dimming control with two separate rows (Case study 3), than one installed in rooms with larger windows and less efficient control systems (case studies 1 and 2).

Table 15. Net present value in 10 years according to different lighting smart controls in London.

NET PRESENT VALUE IN 10 YEARS											
London											
		Width	12.0 m	8.0 m	4.0 m	12.0 m	8.0 m	4.0 m	12.0 m	8.0 m	4.0 m
Depth	Window-to-Façade Ratio	Reflec-tance	Case Study 3: Dimming Control with Two Separate Rows			Case Study 2: Dimming Control for All Luminaires			Case Study 1: On/Off Control with Two Separate Rows		
3.0 m	30%	High	-	-	-	158 €	60 €	−39 €	-	-	-
3.0 m	60%	High	-	-	-	66 €	−2 €	−69 €	-	-	-
3.0 m	90%	High	-	-	-	29 €	−26 €	−82 €	-	-	-
3.0 m	30%	Low	-	-	-	328 €	173 €	18 €	-	-	-
3.0 m	60%	Low	-	-	-	173 €	70 €	−34 €	-	-	-
3.0 m	90%	Low	-	-	-	107 €	25 €	−56 €	-	-	-
6.0 m	30%	High	1453 €	881 €	309 €	1229 €	773 €	318 €	554 €	351 €	148 €
6.0 m	60%	High	733 €	401 €	69 €	675 €	404 €	134 €	240 €	142 €	43 €
6.0 m	90%	High	493 €	241 €	−11 €	490 €	281 €	72 €	185 €	105 €	25 €
6.0 m	30%	Low	1442 €	873 €	305 €	970 €	601 €	232 €	322 €	196 €	71 €
6.0 m	60%	Low	1818 €	1124 €	431 €	1502 €	956 €	409 €	787 €	506 €	226 €
6.0 m	90%	Low	1154 €	682 €	209 €	970 €	601 €	232 €	477 €	299 €	122 €
9.0 m	30%	High	1453 €	881 €	309 €	804 €	490 €	177 €	591 €	376 €	160 €
9.0 m	60%	High	2357 €	1484 €	610 €	1912 €	1229 €	546 €	886 €	573 €	259 €
9.0 m	90%	High	1933 €	1201 €	469 €	1635 €	1044 €	454 €	720 €	462 €	203 €
9.0 m	30%	Low	1353 €	814 €	276 €	527 €	306 €	84 €	366 €	226 €	85 €
9.0 m	60%	Low	2151 €	1346 €	541 €	1258 €	793 €	328 €	986 €	639 €	292 €
9.0 m	90%	Low	2682 €	1700 €	718 €	1856 €	1192 €	527 €	1207 €	787 €	366 €

5.3. Cost Effectiveness in Madrid

The PP results for Madrid are shown in Table 16. As in Table 4, the annual electric cost in 2016 (EC2016) in Spain is the highest of the three locations under study and, although its annual growth rate is not the highest, the electric energy cost forecast obtained remains higher than in the United Kingdom and Sweden. Accordingly, the lighting smart controls promote greater economic savings. As in the previous locations studied, there is adequate profitability for the three lighting control systems installed in rooms 6.00 m deep or more (PP average value of 3.1 years compared to 17.5 years), especially when the rooms are at least 8.00 m wide (PP average value of 2.3 years in the case of 3.00 m deep). There is also an average PP decrease of 28.5% and 6.1% compared to Stockholm and London, respectively.

Table 16. Payback period according to different lighting smart controls in Madrid.

PAYBACK PERIOD											
Madrid											
		Width	12.0 m	8.0 m	4.0 m	12.0 m	8.0 m	4.0 m	12.0 m	8.0 m	4.0 m
Depth	Window-to-Façade Ratio	Reflec-tance	Case Study 3: Dimming Control with Two Separate Rows			Case Study 2: Dimming Control for All Luminaires			Case Study 1: On/Off Control with Two Separate Rows		
3.0 m	30%	High	-	-	-	9 years	12 years	19 years	-	-	-
3.0 m	60%	High	-	-	-	15 years	19 years	30 years	-	-	-
3.0 m	90%	High	-	-	-	18 years	23 years	35 years	-	-	-
3.0 m	30%	Low	-	-	-	5 years	7 years	11 years	-	-	-
3.0 m	60%	Low	-	-	-	9 years	13 years	21 years	-	-	-
3.0 m	90%	Low	-	-	-	16 years	21 years	32 years	-	-	-
6.0 m	30%	High	2 years	3 years	5 years	1 years	2 years	3 years	1 years	2 years	3 years
6.0 m	60%	High	5 years	7 years	12 years	3 years	5 years	8 years	3 years	5 years	8 years
6.0 m	90%	High	8 years	11 years	18 years	5 years	7 years	12 years	5 years	7 years	12 years
6.0 m	30%	Low	2 years	2 years	4 years	1 years	2 years	3 years	1 years	1 years	2 years
6.0 m	60%	Low	2 years	3 years	5 years	1 years	2 years	3 years	1 years	1 years	2 years
6.0 m	90%	Low	3 years	4 years	8 years	2 years	3 years	5 years	2 years	2 years	4 years
9.0 m	30%	High	2 years	2 years	4 years	1 years	2 years	3 years	1 years	1 years	2 years
9.0 m	60%	High	1 years	2 years	3 years	1 years	1 years	2 years	1 years	1 years	2 years
9.0 m	90%	High	2 years	3 years	5 years	2 years	2 years	4 years	1 years	2 years	3 years
9.0 m	30%	Low	2 years	2 years	4 years	2 years	2 years	4 years	1 years	1 years	2 years
9.0 m	60%	Low	1 years	2 years	3 years	1 years	1 years	2 years	1 years	1 years	1 years
9.0 m	90%	Low	1 years	1 years	2 years	1 years	1 years	2 years	1 years	1 years	1 years

As in the other two locations, Table 17 shows that the use of lighting control systems starts to be profitable for rooms 6.00 m deep or more (average NPV10 of 940.22 €, an increase of 88.8% and

35.6% compared to Stockholm and London, respectively), obtaining the highest economic savings for rooms 8.00 m wide or more (average NPV10 of 1209.58 €, an increase of 81.0% and 33.7%, respectively), especially for rooms 9.00 m deep. In the same way, the greatest economic savings after 10 years are obtained when smart systems are used, with an average NPV10 improvement compared to case 1, of 74% for case 2 and 123% for case 3. Thus, given that the Spanish electric energy cost forecast is the highest of the three locations under study, and that Madrid is the location with the highest annual energy saving in the deepest rooms, the economic saving increases using the systems from cases 2 and 3 in these wide, deep rooms was 82.6% and 79.4% compared to Stockholm, and 35.4% and 27.5% compared to London, respectively.

As shown in the case of Stockholm and London, using smart systems in rooms at least 8.00 m wide with small windows is more profitable than installing manual On/Off control systems with two separate rows, except in the case of deep rooms with dark surfaces.

According to the results for the three locations above, it can be concluded that for rooms at least 6.00 m deep and 8.00 m wide, the more complex the control system, the greater the profitability obtained after 10 years. Moreover, due to the higher initial investment costs of the smart control systems, the simpler the control system, the sooner the cost is amortized.

Table 17. Net present value in 10 years according to different lighting smart controls in Madrid.

NET PRESENT VALUE IN 10 YEARS											
Madrid											
NPV		Width	12.0 m	8.0 m	4.0 m	12.0 m	8.0 m	4.0 m	12.0 m	8.0 m	4.0 m
Depth	Window-to-Façade Ratio	Reflec-tance	Case Study 3: Dimming Control with Two Separate Rows			Case Study 2: Dimming Control for All Luminaires			Case Study 1: On/Off Control with Two Separate Rows		
3.0 m	30%	High	-	-	-	36 €	−17 €	−70 €	-	-	-
3.0 m	60%	High	-	-	-	−43 €	−70 €	−96 €	-	-	-
3.0 m	90%	High	-	-	-	−63 €	−83 €	−103 €	-	-	-
3.0 m	30%	Low	-	-	-	210 €	99 €	−12 €	-	-	-
3.0 m	60%	Low	-	-	-	20 €	−27 €	−75 €	-	-	-
3.0 m	90%	Low	-	-	-	−51 €	−75 €	−99 €	-	-	-
6.0 m	30%	High	1716 €	1063 €	410 €	1540 €	986 €	432 €	745 €	482 €	218 €
6.0 m	60%	High	350 €	152 €	−45 €	392 €	221 €	49 €	152 €	86 €	20 €
6.0 m	90%	High	113 €	−6 €	−125 €	194 €	89 €	−17 €	72 €	33 €	−7 €
6.0 m	30%	Low	2488 €	1577 €	667 €	1825 €	1176 €	527 €	927 €	603 €	278 €
6.0 m	60%	Low	1752 €	1087 €	422 €	1540 €	986 €	432 €	856 €	555 €	255 €
6.0 m	90%	Low	802 €	453 €	105 €	733 €	448 €	163 €	405 €	255 €	104 €
9.0 m	30%	High	2547 €	1617 €	687 €	1659 €	1065 €	471 €	1201 €	785 €	369 €
9.0 m	60%	High	2824 €	1802 €	779 €	2490 €	1619 €	748 €	1121 €	732 €	343 €
9.0 m	90%	High	1439 €	878 €	317 €	1303 €	828 €	353 €	587 €	376 €	165 €
9.0 m	30%	Low	2298 €	1451 €	604 €	1018 €	638 €	258 €	951 €	619 €	286 €
9.0 m	60%	Low	3438 €	2211 €	984 €	2371 €	1540 €	709 €	1711 €	1125 €	540 €
9.0 m	90%	Low	4269 €	2765 €	1261 €	3511 €	2300 €	1089 €	1901 €	1252 €	603 €

6. Conclusions

Building design is currently moving towards a new age of efficient construction, using cutting-edge technologies to promote higher energy efficiency. In the field of lighting, the use of smart controls is key to reducing electricity consumption. Therefore, dynamic daylight metrics are useful tools for determining the energy savings obtained using different smart controls.

As deduced from Section 3 on the quantification of power consumption, except for deep rooms with low reflectance, large windows (window-to-façade ratio of 90%) save between 40% and 60% more energy compared to small windows (window-to-façade ratio of 30%). Moreover, medium windows (window-to-façade ratio of 60%) use 20–40% less energy in lighting than small windows. The impact of a large window on energy efficiency is higher in sites with better weather conditions.

Smart controls noticeably reduce power consumption in electric lighting. Dimming controls (Case study 2) in particular save almost 30% energy compared to the conventional On/Off control (Case study 0). In addition, the switching control with separate rows (Case study 1) saves up to 20% energy. Combining both strategies, the dimming controls with separate rows of luminaires (Case study 3) save between 35% and 55% more than the typical On/Off control (Case study 0). This applies to all latitudes studied.

Using smart controls, energy saving is higher for cases with small windows due to the dependence on electric lighting. Deep rooms, where the typical switch control is almost always on, are the exception, regardless of window size. Moreover, smaller windows, which consume less energy in electric lighting, can compensate for this weak point using smart controls.

In studying energy efficiency based on room depth, energy saving in Madrid is noticeably lower than in London or Stockholm for rooms 3.00 m deep, resulting in an average of 40% less than in the other locations. However, the deeper rooms in Madrid improved energy saving by almost 40% compared to other sites. The results obtained for Madrid are also particularly unique due to the high illuminance caused by daylight and the high cost of energy in Spain. Therefore, it can be concluded that, considering a depth greater than 6.00 m, the greater the sky luminance, the higher the energy savings with lighting smart controls. The opposite is true of rooms 6.00 m deep or less. As explained in the methodology, the results obtained for Madrid could be extrapolated to the Mediterranean climate, while the conclusions for London and Stockholm could be assumed for other locations in Northern Europe.

As seen in Section 4 on the profitability of the proposed smart controls, suitable payback periods (PPs) can be achieved for the three control systems in rooms 6.00 m deep or more (PP average value from 3.1 to 4.5 years), but not for rooms 3.00 m deep (PP average value from 10.1 to 18.6 years) while in rooms 6.00 m deep or more and 8.00 m wide or more, the PP decreases noticeably (PP average value from 2.3 to 3.3 years). It is worth noting that according to the sky conditions and the electric energy cost considered, the best PP is observed for Madrid, while the least favorable value is seen for Stockholm.

The final analysis is net present value (NPV10), used to determine the economic benefits obtained after 10 years due to the energy saving. Unlike payback periods, the NPV10 shows that in larger rooms, the more complex the control system, the greater the economic benefits obtained after 10 years. Using a dimming control (Case study 2) instead of a switch control with two separate rows (Case study 1) finally saves an average of between 73% and 88%, depending on the location. Moreover, using a dimming system with separate rows (Case study 3) rather than an On/Off control with separate rows (Case study 1) produces a final average benefit between 126% and 156%.

In conclusion, the previous statements demonstrate the high energy efficiency and the economic profitability of lighting smart controls, and the undeniable usefulness of the dimming systems controlled by illuminance-meters in different scenarios.

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