applied sciences

Article

Partial Daylight Autonomy (DAp): A New Lighting Dynamic Metric to Optimize the Design of Windows for Seasonal Use Spaces

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Featured Application: This study proposes a new daylight dynamic metric which serves to quantify more accurately the energy consumption of electric lighting for spaces with seasonal use, optimizing the window design.

Abstract: Nowadays, daylight dynamic metrics are the most useful indicators to quantify the use of natural light, with daylight autonomy (DA) being one of the most widespread among all of them. This metric represents the percentage of the occupied time throughout the year in an indoor space when daylight reaches the minimum illuminance level to develop a specific task. Accordingly, the higher the percentage of DA, the shorter the switching on time of electric lighting. However, this metric considers for its calculations all business days of a whole standard year, and is thus not an accurate indicator for seasonal use spaces such as school classrooms. In this context, a variant of this metric is proposed, namely partial daylight autonomy (DAp), which is a non-lineal derivation of DA that considers those seasonal use spaces, helping to define the real percentage of indoor daylight use in order to properly quantify the accurate switching on time of electric lighting and therefore its energy consumption. As deduced from the analysis, the more precise results provided by DAp reach divergences close to 10% in comparison with the original conception of DA. Thus, this metric serves to estimate more accurately the impact on energy consumption if an electric lighting control system is implemented through lux meters. This new proposal has been monitored under real sky conditions in a test cell, providing converging results with those observed in the simulation process.

Keywords: dynamic metric; daylight autonomy; partial daylight autonomy; energy consumption; window design

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Citation: Ruiz, A.; Campano, M.Á.; Acosta, I.; Luque, Ó. Partial Daylight Autonomy (DAp): A New Lighting Dynamic Metric to Optimize the Design of Windows for Seasonal Use Spaces. *Appl. Sci.* **2021**, *11*, 8228. https://doi.org/10.3390/app11178228

Academic Editors: Marina Bonomolo and Francesca Fragliasso

Received: 15 July 2021
Accepted: 31 August 2021
Published: 4 September 2021

1. Introduction

Nowadays, building design pays special attention to the reduction of operational energy consumption. Given this context, electric lighting represents up to 30% of the total energy consumption in buildings, according to the climate and building function [1,2]. Thus, a suitable use of daylight must be promoted in the current architectural design, by means of a passive design of the building's envelope [3,4] or by using new technologies, such as occupant detectors [5], daylight-linked controls [6], and algorithms defined by lighting calculations [7,8], in accordance with the illuminance needs while glare and sunlight are avoided [9].

The daylight metrics serve to quantify the energy savings provided by a proper window [10,11] or skylight [4] design, according to the potential use of natural light and the switching off or dimming of the lighting fixtures. The most widespread concept in this context is the daylight factor (DF), which is the ratio of the illuminance level inside a given room to the illuminance level outside, determining the potential use of the natural source at a given indoor point under overcast sky conditions [12]. DF is defined as a static metric, since the calculation scenario has an invariant luminance distribution regardless of the solar altitude, as location and orientation are irrelevant considering an ideal overcast sky [13]. Accordingly, the indoor illuminance at a given point can be quantified knowing the outdoor illuminance. This concept has served as a useful tool to determine the proper design of architectural features [14,15] to provide a suitable amount of natural light.

Despite its usefulness, DF cannot be applied for determining the energy consumption of electric lighting, since this metric ignores the dynamic variation of the sky, as well as the illuminance requirements to carry out the tasks [16]. Given this context, the dynamic metrics arose, as these tools quantify the energy savings based on location, window orientation and the luminous distribution of the sky vault in accordance with statistical weather data. Daylight autonomy (DA) is the most common dynamic metric. This concept was proposed in 1989 by the Association Suisse des Electriciens [17] and subsequently redefined by Reinhart et al. [18]. DA is defined as the percentage of the time fraction during the year when an illuminance threshold is met by daylight alone. Therefore, the higher the metric value, the shorter the switching on time of electric lighting.

According to this definition, a limitation of its application arises, given that the chosen lighting schedules just can represent users behavior probabilistically [19]. This affects not only to the behavior of the building in use, but also to those periods in which the building is unoccupied, such as during holidays. On the other hand, the validation of dynamic metrics in real conditions is complex due to the difficulties derived from monitoring illuminance in occupied rooms for a prolonged period [20]. In this way, there are several studies that have analyzed the divergences between the simulation and monitoring of dynamic metrics using spaces without occupancy, obtaining divergences below 10% [21,22].

Two main metrics have evolved from the original conception of DA, with similar limitations. The variation proposed by Rogers et al. [18] is the continuous daylight autonomy (DAcon), defined as the occupied time throughout the year when a threshold is met by daylight, considering a partial credit linearly to values below the threshold defined, in accordance with the adaptive capacity of human vision. This definition is not commonly used [23], despite its usefulness in quantifying the energy consumption provided by a dimmer control [24]. The second variation, proposed by Acosta et al. [8], corresponds to the minimum daylight autonomy (DAm) which determines the percentage of the occupied time when the required illuminance value is met by natural light under the most common worst case scenario, overcast sky conditions. This metric, developed by Acosta et al., arose with the aim of bridging the gap between static metrics such as DF and dynamic metrics.

One of the most interesting dynamic metrics is useful daylight illuminance (UDI), which quantifies the time fraction when daylight levels are appropriate for occupants [25,26]. Nabil et al. developed this usefulness concept, determining the percentage of the occupied time when the illuminance is suitable, between 100 and 3000 lx, falling short, below 100 lx, or too high, at over 3000 lx.

Most recently, there is a trend that has led to the development of dynamic metrics not only linked to a determined time frame, but also to the occupied space. Accordingly, the spatial metrics provide a score to the studied surface—either a room or an entire building—ignoring the quantification of the daylight use in a specific point. Given this context, the Illuminating Engineering Society of North America (IESNA) proposed spatial daylight autonomy (sDA), which determines the fraction of the work plane where the illuminance value is higher than or equal to a certain value, usually 300 lux, during at least 50% of the annual occupied hours [27], giving a unique score for the entire room.

However, despite the noticeable variety of daylight dynamic metrics and the existence of studies analyzing differences of daylight characteristics between summer and winter in offices, as the study carried out by Bellia et al. [28], there is not an accurate procedure to quantify the energy savings allowed by a rational use of electric lighting in seasonal use spaces, such as educational buildings. Thus, the adaptation of DA to this type of buildings can serve to provide a better approximation of the operational lighting energy.

Aim and Objectives

Given the scenario described in the state of the art, a variation of DA is proposed, with the aim to accurately quantify the daylight use in seasonal spaces. This new concept is defined as partial daylight autonomy (DAp).

The calculation procedure of the proposed metric is firstly defined, in order to implement this new concept as a plug-in for current lighting simulation software. Subsequently, the metric is validated by means of a test cell under real sky conditions [29], which serves to quantify the dynamic metrics under statistical weather data. Finally, the results of DA and DAp are compared for a virtual classroom considering different variables, such as the window size, the illuminance threshold and the excluded time interval, demonstrating that there is a clear divergence between these metrics as well as the suitability of DAp for seasonal use spaces. In this way, DAp provides a more precise quantification of the benefits promoted by daylight for seasonal use spaces, such as educational buildings. Considering the particular case of a school, the higher performance of daylight during summer should be ignored due to the vacations during that period. Thus, the real autonomy of daylight is actually lower than that determined by the classical metric of DA.

2. Materials and Methods

2.1. Definition of DAp

DAp is defined as the time fraction of the occupied time throughout the year, considering the seasonal use of the studied venue, during which a certain illuminance threshold is met by daylight alone. Accordingly, the higher the DAp value, the lower the energy consumption of electric lighting. A value close to 1 represents a high independence of electric lighting, while a result near 0 shows the opposite. Thus, this metric can be expressed as (1):

$$DAp = \frac{\sum_{i=1}^{n} w_{fi} \cdot t_i}{\sum_{i=1}^{n} t_i} \in [0,\ 1] \qquad wf_i = \begin{cases} 1\ if\ E_D \geq E_T \\ 0\ if\ E_D < E_T \end{cases} \tag{1}$$

where w_{fi} represents the weighting factor that depends on the relationship between the illuminance threshold and the lighting value achieved by daylight, t_i is the time fraction which corresponds to a certain illuminance value, according to a time interval throughout the year, E_D is the daylight illuminance reached at the studied point and linked to a specific time fraction, and E_T is the illuminance threshold defined for the task development.

Given this definition, it can be deduced that DA and DAp metrics also allow the quantification of the energy consumption of electric lighting, concluding the time throughout the year during which the luminaires should switch on to guarantee the illuminance threshold. Therefore, the higher the DA and DAp values, the lower the power consumption of electric lighting.

As in the case of DA, DAp value also depends on the number of occupancy hours per day. In addition, the difference between DA and DAp is that while the former considers the statistical climate data throughout the whole year, the latter takes into account the time interval during the year when the studied venue is occupied. Thus, a more accurate calculation is provided for seasonal use spaces. Figure 1 shows the graphical representation of both concepts. In addition, this new metric has two limitations. First of all, it cannot be applied in buildings in constant use throughout the year, where the use of DA is more appropriate. In addition, as in the case of the rest of dynamic metrics, DAp depends on statistical climate data and complex lighting calculations, which could not be perfectly accurate in a real environment.

Following the representation of DA, this new concept determines the illuminance threshold in its subscript, followed by the time interval of the metric application in days of the year. Accordingly, $DAp_{500[243–182]}$ defines the daylight autonomy for a threshold of 500 lx and a calculation interval from 31 August (day 243) to 1 July (day 182).

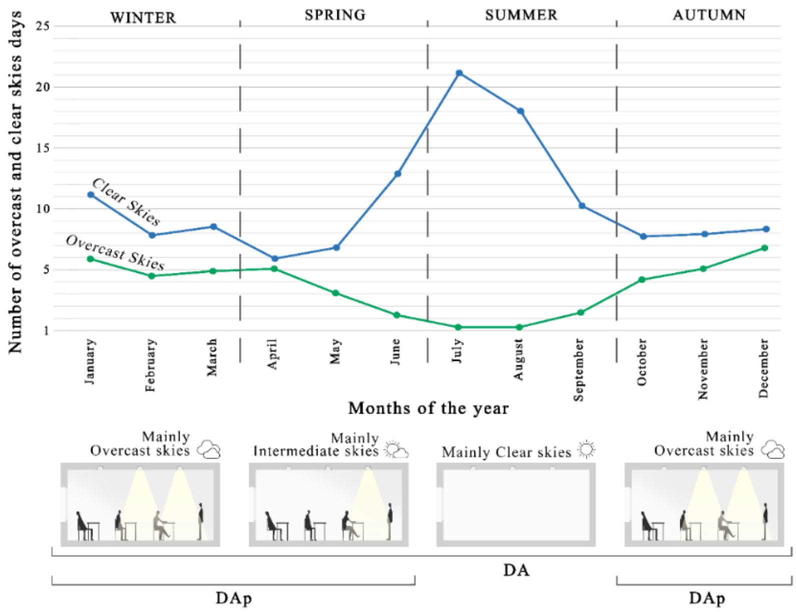

Figure 1. Graphical representation of DA and DAp for a seasonal use space (example of space located in Madrid, Spain, with mainly clear skies).

2.2. Parameters of the Calculation Program

The simulation software used for the dynamic metric calculation is DIVA for Rhino, which is based on the RADIANCE engine, using the daylight coefficients [30,31] in combination with the All-weather sky model [32] to predict the indoor daylight according to statistical weather data. DIVA is an evolution of the previous software DAYSIM, developed by the Sustainable Lab of the Massachusetts Institute of Technology [33], although implemented in the modeling program Rhino 6. The accuracy of this calculation program has been validated by several researchers, demonstrating realistic results not only for the sky and reflected components [34,35], but also for the dynamic metrics [22]. The calculation parameters are shown in Table 1, using an illuminance simulation interval of 5 min for the whole year.

Table 1. Parameters of the calculation program [36,37].

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

2.3. Validation of the Modelling Tool

The validation of the modelling tool results is carried out by means of a comparison process, in which the illuminance values obtained by simulation are checked with those measured in an experimental test cell, used as a base model for the calculation parameters.

2.3.1. Description of the Experimental Test Cell and Boundary Conditions

The experimental test cell [21,29] used as a comparison model is located in Seville (Spain), which is 2.40 m wide, 3.20 m deep, and 2.70 m high, as can be seen in Figure 2A. It has a single window facing south, 116 cm wide by 100 cm high, with 4.8.4 double glazing and a solar factor of 0.75. The reflectance of the inner envelope is 0.72 for walls and ceiling, as well as 0.22 for the floor. Illuminance monitoring was performed throughout 2017 using 8 Delta Ohm HD 2021T illuminance-meters (20–2000 lx ±3.0%), placed at ground level, at 0.40 m each on the axis of symmetry, as Figure 2B shows.

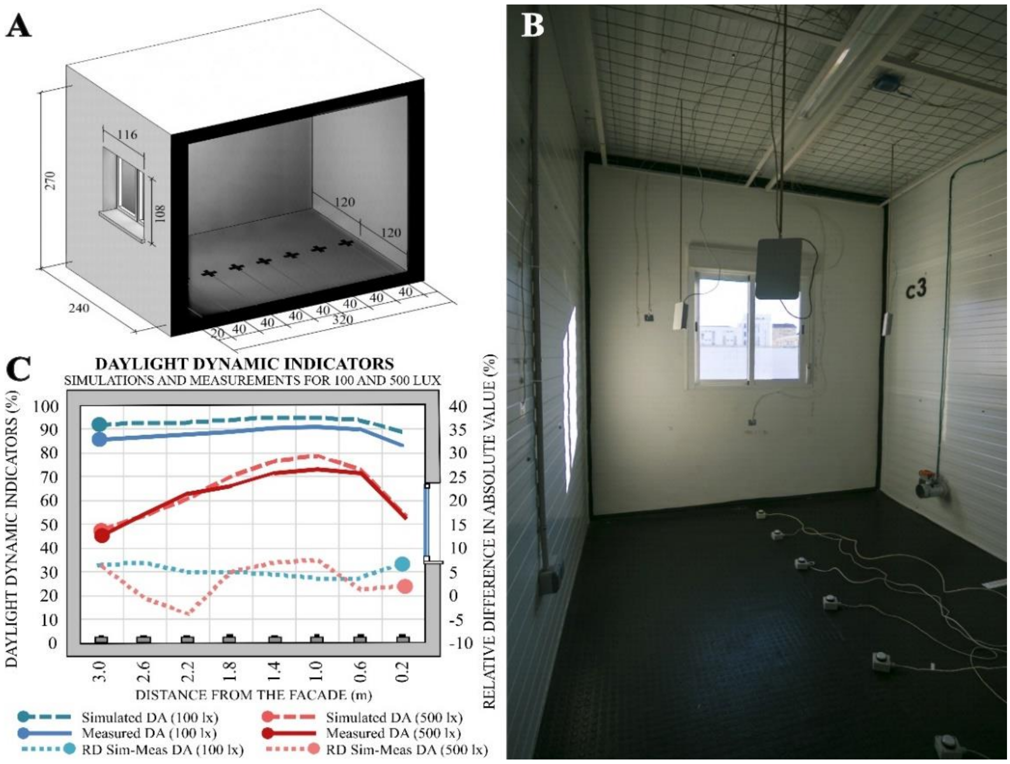

Figure 2. (**A**) Size of the test cell and distribution of illuminance-meters—(**B**) Inner view of the test cell—(**C**) DA results calculated both from illuminance measurements and simulations, including Relative Difference (RD) between them.

The occupancy schedule for DA calculations, both from simulation and measurement values, was from 8:00 to 17:00 on weekdays, using 100 and 500 lx illuminance thresholds.

2.3.2. Results of the Comparison Trials

Figure 2C shows the DA values obtained from virtual model simulation and test cell measurements, both for 100 and 500 lx illuminance thresholds. The highest maximum deviations between DA values from simulations and measurements are of 7.1% and 7.4% with the 100 and 500 lx thresholds, with divergences under 10% in both cases. The bias error values for DA_{100lx} and DA_{500lx} are 5.42% and 3.08% respectively, while the standard deviations (95% reliability) are 2.55% for 100 lx and 8.03% for 500 lx, which are below the 10% of deviation and therefore acceptable.

These results, as well those previously published [8,24,38], show that DIVA-for-Rhino can calculate DA dynamic metric with accurate results for indoor spaces with similar size and boundary conditions, so it can provide a reliable calculation for DAp metric.

3. Base Model of Study and Hypotheses Under Analysis

3.1. Characteristics of the Room Model

With the aim to quantify the divergence of DA and DAp under different scenarios and subsequently to the validation process, a simulation procedure is carried out. A virtual venue measuring 6.00 m wide, 8.00 m in length, and 3.0 m high, corresponding with the typical dimensions for a Spanish classroom, was defined according to regional standards [39] and to a characterization of existing educational buildings [40] to analyze both dynamic metrics. A window of variable size (window-to-wall ratio (WWR) of 30%, 45%, and 60%) is located in one of the facades. The window glazing has an optical transmittance of 0.75. The inner surfaces of the studied model act as diffuse reflectors, following the Lambertian distribution, where the luminous intensity of the reflected light is proportional to the cosine of the angle between the observer's line of sight and the surface normal. Two average reflectance sets are addressed in the calculation process, considering bright surfaces with high reflectance values and dark surfaces corresponding to low reflectance values. The parameters related with the calculation model are described in Figure 3.

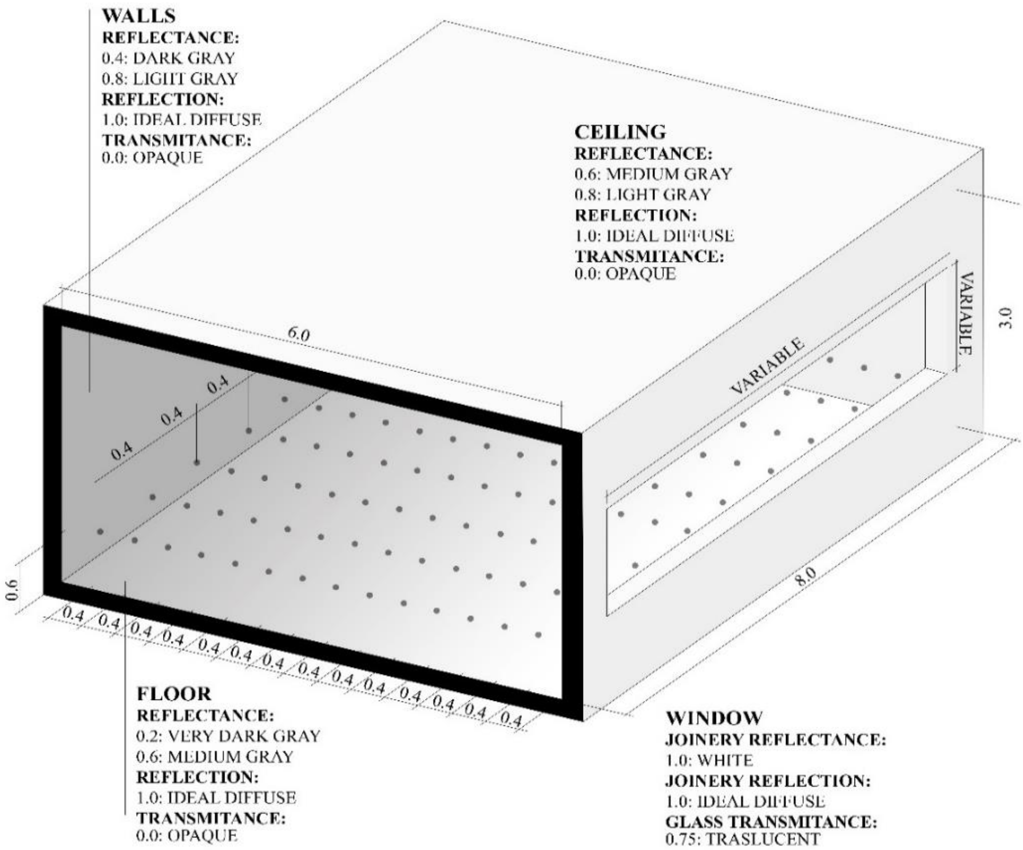

Figure 3. Characteristics of the room model.

The dynamic metrics are quantified on the central axis of the room. As seen in Figure 4, the studied points are located on this axis of the grid (Y = 4.0 m) with a spacing of 0.40 m from each other and at 0.60 m above the floor, based on the usual position of the work plane in a classroom.

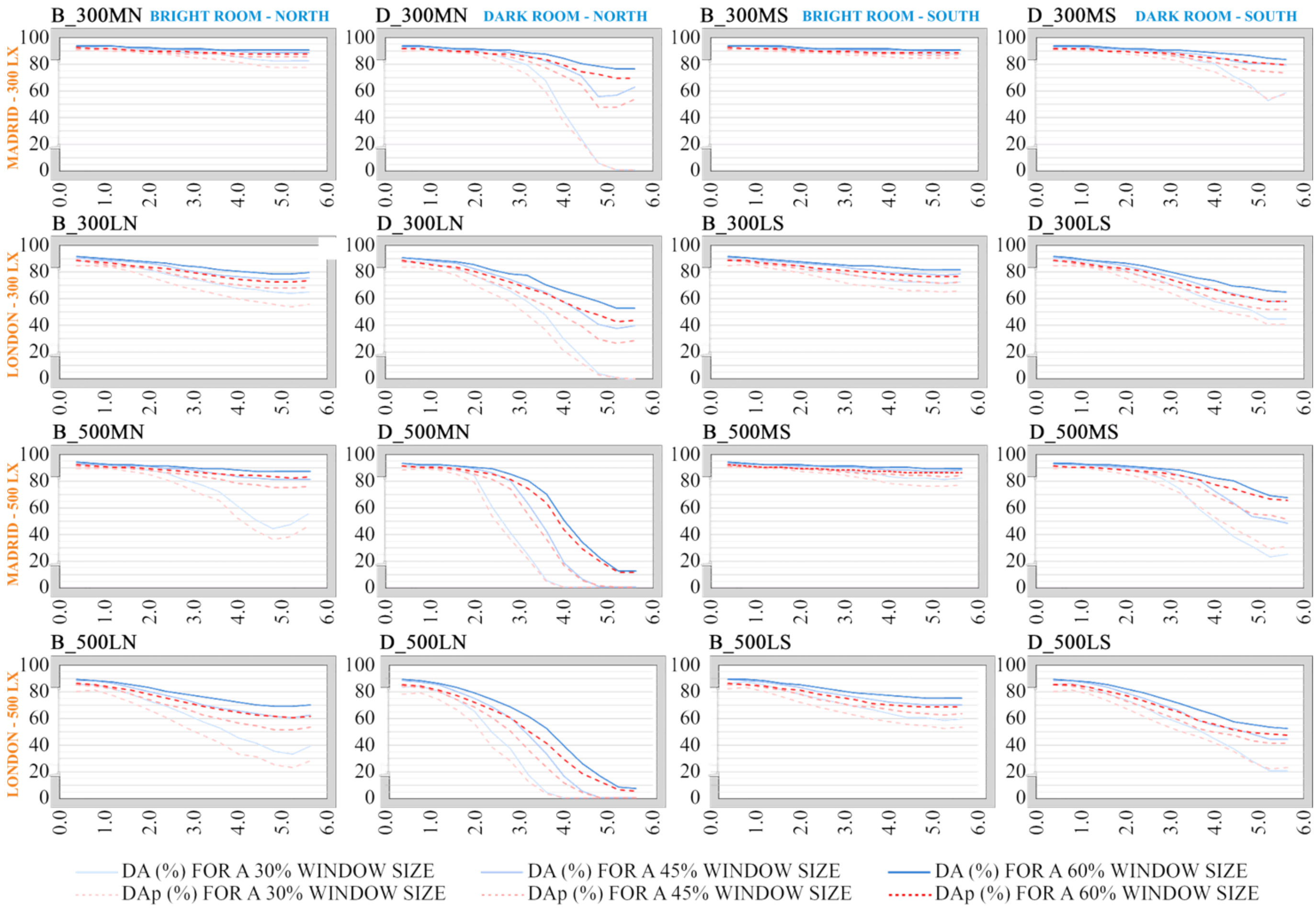

Figure 4. Quantification of DA and DAp in the calculation models according to Window-to-Wall Ratio (WWR).

3.2. Boundary Conditions

Two illuminance thresholds have been considered in the determination of dynamic metrics: 300 and 500 lx, which correspond to typical requirements established by the current standards [41], fitting with the usual demand of educational buildings.

The occupancy time considered for both dynamic metrics starts at 8.30 a.m. and finishes at 6.30 p.m., following the utilization of natural light in a conventional educational space. In the case of the determination of DA, all days throughout the year are considered, hence this metric is only defined by the illuminance threshold, i.e., DA_{300} and DA_{500}. Considering the calculation of DAp, the lighting requirements are the same as in the previous metric, although the time interval from July 1st to August 31st is excluded, coinciding with the typical summer holidays for educational buildings of Southern Europe. Accordingly, this dynamic concept is defined as $DAp_{300[243–182]}$ and $DAp_{500[243–182]}$.

Two locations are considered for the quantification of DAp in the calculation model, using the same spatial characteristics for the classroom (a Spanish multipurpose classroom) in both cases, to be able to analyze the variations due exclusively to sky and latitude conditions. The first one corresponds to Madrid (Spain) at 40° north latitude with mainly clear skies. The second location is London (UK) at 50° north latitude under predominantly overcast skies. Both cities represent typical weather scenarios in Europe, defining opposite cases. The Energy Plus reference [42] provides the weather data for both locations, according to the relationship between normal and diffuse horizontal irradiances and the sky models defined by Perez et al. [32] and accepted by the CIE [43]. Both sky parameter definitions, clear sky and overcast sky, are those described by the CIE [13,43].

The window facing is also decisive in the dynamic metrics quantification. Two orientations were considered for carrying out the simulations for quantifying the divergence between DA and DAp. According to the northern locations described above, a North orientation provides the worst case scenario for using the natural light, while windows facing South usually allow the maximum use of daylight [44].

Table 2 summarizes the calculation parameters, defining the name model in accordance with the defined variables.

Table 2. Calculation models according to defined variables.

Model	Window-to-Wall Ratio (%)	Reflectance (%) Ceiling	Reflectance (%) Floor	Reflectance (%) Walls	Illuminance Threshold (lx)	Location	Window Orientation
30B_300MN	30	0.80	0.60	0.80	300	Madrid	North
30D_300MN	30	0.60	0.20	0.40	300	Madrid	North
30B_500MN	30	0.80	0.60	0.80	500	Madrid	North
30D_500MN	30	0.60	0.20	0.40	500	Madrid	North
45B_300MN	45	0.80	0.60	0.80	300	Madrid	North
45D_300MN	45	0.60	0.20	0.40	300	Madrid	North
45B_500MN	45	0.80	0.60	0.80	500	Madrid	North
45D_500MN	45	0.60	0.20	0.40	500	Madrid	North
60B_300MN	60	0.80	0.60	0.80	300	Madrid	North
60D_300MN	60	0.60	0.20	0.40	300	Madrid	North
60B_500MN	60	0.80	0.60	0.80	500	Madrid	North
60D_500MN	60	0.60	0.20	0.40	500	Madrid	North
30B_300MS	30	0.80	0.60	0.80	300	Madrid	South
30D_300MS	30	0.60	0.20	0.40	300	Madrid	South
30B_500MS	30	0.80	0.60	0.80	500	Madrid	South
30D_500MS	30	0.60	0.20	0.40	500	Madrid	South
45B_300MS	45	0.80	0.60	0.80	300	Madrid	South
45D_300MS	45	0.60	0.20	0.40	300	Madrid	South
45B_500MS	45	0.80	0.60	0.80	500	Madrid	South
45D_500MS	45	0.60	0.20	0.40	500	Madrid	South
60B_300MS	60	0.80	0.60	0.80	300	Madrid	South
60D_300MS	60	0.60	0.20	0.40	300	Madrid	South
60B_500MS	60	0.80	0.60	0.80	500	Madrid	South
60D_500MS	60	0.60	0.20	0.40	500	Madrid	South
30B_300LN	30	0.80	0.60	0.80	300	London	North
30D_300LN	30	0.60	0.20	0.40	300	London	North
30B_500LN	30	0.80	0.60	0.80	500	London	North
30D_500LN	30	0.60	0.20	0.40	500	London	North
45B_300LN	45	0.80	0.60	0.80	300	London	North
45D_300LN	45	0.60	0.20	0.40	300	London	North
45B_500LN	45	0.80	0.60	0.80	500	London	North
45D_500LN	45	0.60	0.20	0.40	500	London	North
60B_300LN	60	0.80	0.60	0.80	300	London	North
60D_300LN	60	0.60	0.20	0.40	300	London	North
60B_500LN	60	0.80	0.60	0.80	500	London	North
60D_500LN	60	0.60	0.20	0.40	500	London	North
30B_300LS	30	0.80	0.60	0.80	300	London	South
30D_300LS	30	0.60	0.20	0.40	300	London	South
30B_500LS	30	0.80	0.60	0.80	500	London	South
30D_500LS	30	0.60	0.20	0.40	500	London	South
45B_300LS	45	0.80	0.60	0.80	300	London	South
45D_300LS	45	0.60	0.20	0.40	300	London	South
45B_500LS	45	0.80	0.60	0.80	500	London	South
45D_500LS	45	0.60	0.20	0.40	500	London	South
60B_300LS	60	0.80	0.60	0.80	300	London	South
60D_300LS	60	0.60	0.20	0.40	300	London	South
60B_500LS	60	0.80	0.60	0.80	500	London	South
60D_500LS	60	0.60	0.20	0.40	500	London	South

4. Analysis of Results and Discussion

The analysis of the divergence between DA and DAp metrics is performed by modifying different variables of the calculation model, such as the window size and orientation, the reflectance of the inner surfaces of the room, its location, and finally the illuminance requirements.

4.1. Divergence of DA and DAp According to Window Size

The first analysis addresses the divergence of the studied metrics with respect to the window size. Figure 4 shows the quantification of both metrics considering three window-to-wall ratios: 30%, 45%, and 60%. Odd columns represent bright rooms (B) with a high reflectance value of the inner surfaces, while even columns show dark rooms (D) according to the model described in Figure 4. First and second rows describe the calculation models with an illuminance threshold of 300 lx, while the third and last rows show rooms with a light requirement of 500 lx. Odd columns represent rooms located in Madrid, Spain and even columns show rooms in the London scenario. Finally, the first and second columns represent windows facing North and the third and fourth columns describe windows oriented to the South. The labels located in the left-top of the room sections describe the calculation model according to the parameters defined in Table 2.

As can be observed in Figure 4, there is a significant divergence between the DA and DAp results, mainly in the back of the room. This divergence increases when the illuminance threshold is higher or when the access to natural light is poorer, such as the case of room models in London.

The variation between DA_{300} and $DAp_{300[243–182]}$ varies depending on the window-to-wall ratio. For an opening size of 30%, the mean deviation is 7.50%, reaching a maximum divergence of 18.5% in the back of the room. This difference between the studied metrics increases for a higher illuminance threshold. The mean deviation between DA_{500} and $DAp_{500[243–182]}$ corresponds to 10.6%, while the maximum divergence, also observed in the back of the room is close to 22.2%. The standard deviation for both presented cases is not really high, namely 4.8% in the case of an illuminance threshold of 300 lx and 7.2% for 500 lx. Therefore, it can be concluded that DAp provides an almost constant divergence in comparison with DA, reaching a maximum difference in the zone from 3.00 m to the back of the room. Accordingly, DAp is apparently a useful metric to provide an accurate calculation of the switching on time of the electric lighting, mainly in zones with poorer access to daylight.

The variation between both metrics decreases when the window size is larger and therefore the access to daylight increases. The difference between DA_{300} and $DAp_{300[243–182]}$ for a window size of 45% of the façade corresponds to a mean deviation of 6.8%, slightly lower than in the case of a smaller window. This divergence is also lower for a larger window—with a window-to-wall ratio of 60%—, reaching a value of 5.5%. Therefore, the higher the access to daylight, the lower the difference between DA and Dap, and thus the lower the energy consumption due to electric lighting regarding the DA calculations.

4.2. Divergence of DA and DAp According to Window Orientation

The second analysis assesses the difference between DA and DAp according to the window orientation. Figure 5 shows the results for both metrics in accordance with the methodology described above and taking into account two orientations, North and South. First and second rows describe the calculation models with a window to façade ratio of 30%, while third and fourth rows show medium-size windows and the last two rows describe the results for large openings. Odd columns represent rooms with a high reflectance of the inner surfaces and even columns show rooms with dark surfaces. Odd rows show the results of both metrics for an illuminance threshold of 300 lx, while even rows represent the opposite scenario, with a requirement of 500 lx. As in the previous trial, labels located in the left-top of the room sections describe the calculation model in accordance with parameters defined in Table 2.

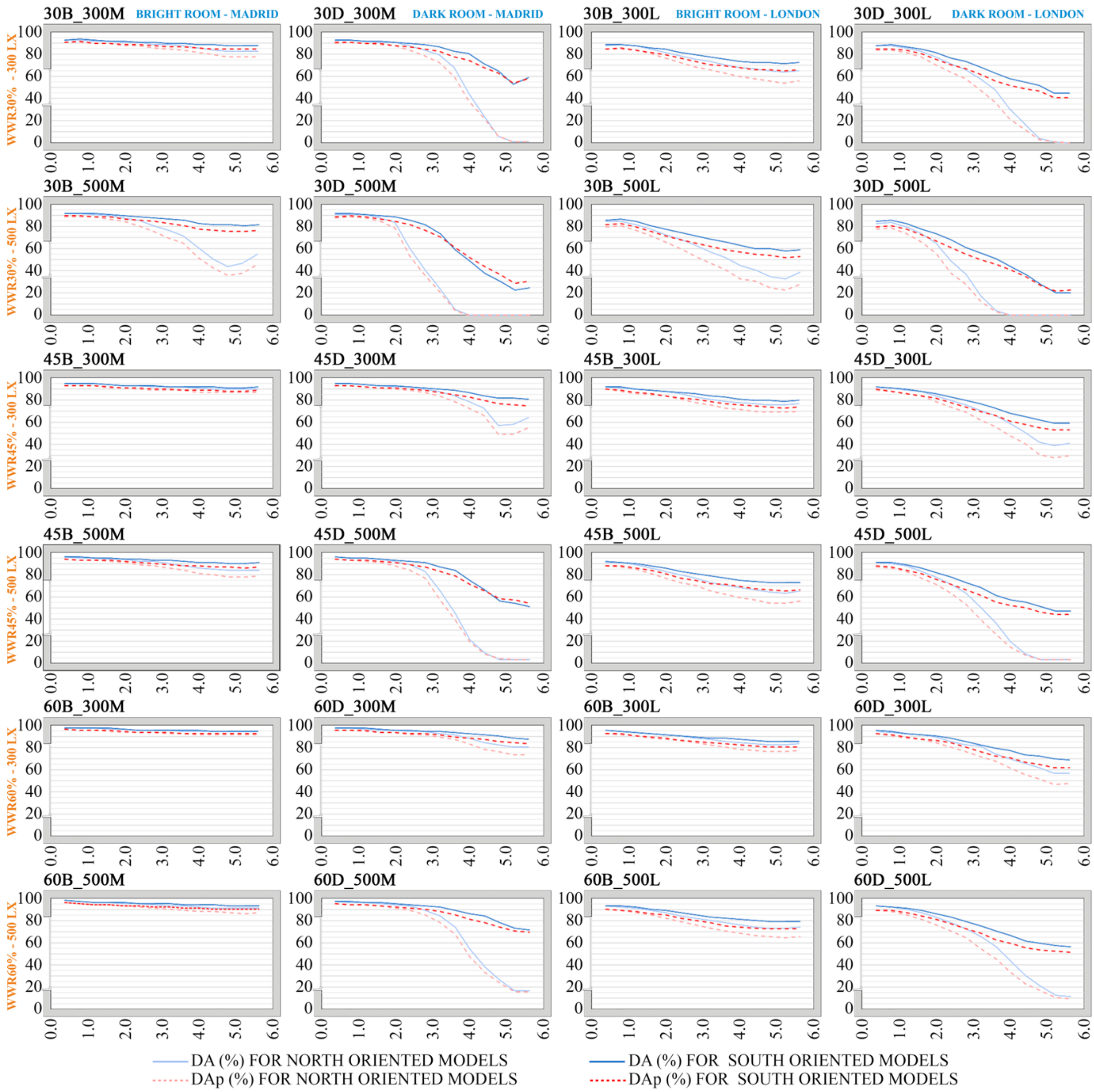

Figure 5. Quantification of DA and DAp in the calculation models according to window orientation.

As deduced from Figure 5, the divergence between DA and DAp also varies depending on the window orientation. As expressed in the previous trial, the poorer the access to natural light, the higher the divergence produced between DAp and DA. Hence, as expected, windows facing North provide a higher difference between both metrics than those facing South. Considering the comparison between DA_{300} and $DAp_{300[243–182]}$, the mean deviation for windows facing North is 8.0%, while this deviation decreases to 5.2% for openings oriented to South. This divergence between metrics increases for an illuminance threshold of 500 lx, with the mean deviation between DA_{500} and $DAp_{500[243–182]}$ of 12.5% for openings oriented to North and 5.6% in the opposite case.

As in the previous trial, the standard deviation is low for both cases, showing a value between 2.4 and 6.5%. Therefore, the difference between DA and DAp is almost constant, except in the case of the zone near the window, where both metrics tend to converge. In the case of the area close to the back of the room, the studied metrics diverge, except when the inner reflectance of the room is low, so it can lead to a higher energy consumption in the back of the room than expected with DA.

Analyzing the DA and DAp values shown in the graphs of the room sections described in Figure 5, it can be concluded that DAp provides a more accurate calculation of the real use of daylight in seasonal use spaces for those cases where the orientation of the window is North. It also can be highlighted that other conditioning factors, such as a low reflectance of the inner surfaces or a small window size, increase the divergence between both metrics and therefore strength the suitability of DAp.

4.3. Divergence of DA and DAp According to Room Reflectance

The third analysis addresses the variation of DAp with respect to DA depending on the reflectance of the inner surfaces of the room. Figure 6 represents the quantification of both metrics, considering the calculation model and boundary conditions described above and taking into account two scenarios; with high (B) and low (D) reflectance values, varying the qualities of the surfaces according to the study cases described in Table 2. As in the previous trial, first and second rows show the room sections with a small window, third and fourth rows show medium-size openings, and the last two rows describe the results for large windows. As in previous studies, labels located in the left-top of the room sections describe the calculation model in accordance with parameters defined in Table 2.

As can be deduced from Figure 6, the divergence between the studied metrics depending on the room reflectance is lower than in the case of the previous trials. This is due to the fact that the room reflectance is a less decisive parameter in the determination of daylight metrics, taking into account the boundary conditions described in the methodology.

According to the previous assertion, it can be noted that the mean deviation between DA_{300} and $DAp_{300[243–182]}$ corresponds to 5.1%, while this value increases up to 8.2% in the case of an illuminance threshold of 500 lx. As can be deduced, the presented deviations are lower than those observed in the trials above, also showing a standard deviation of 2.6% for bright rooms and of 4.7% for dark rooms. Another singularity of this part of the study is that the maximum difference between DA and DAp is not observed in the back of the room, as in the previous cases, but in the center of the room, at a distance between 2 and 4 m from the façade. As deduced from the study cases with windows facing South, both metrics tend to converge in the zone near the façade as well as in the back of the room.

According to this, it can be concluded that the reflectance of the inner surfaces is not a decisive parameter to determine the difference between both metrics.

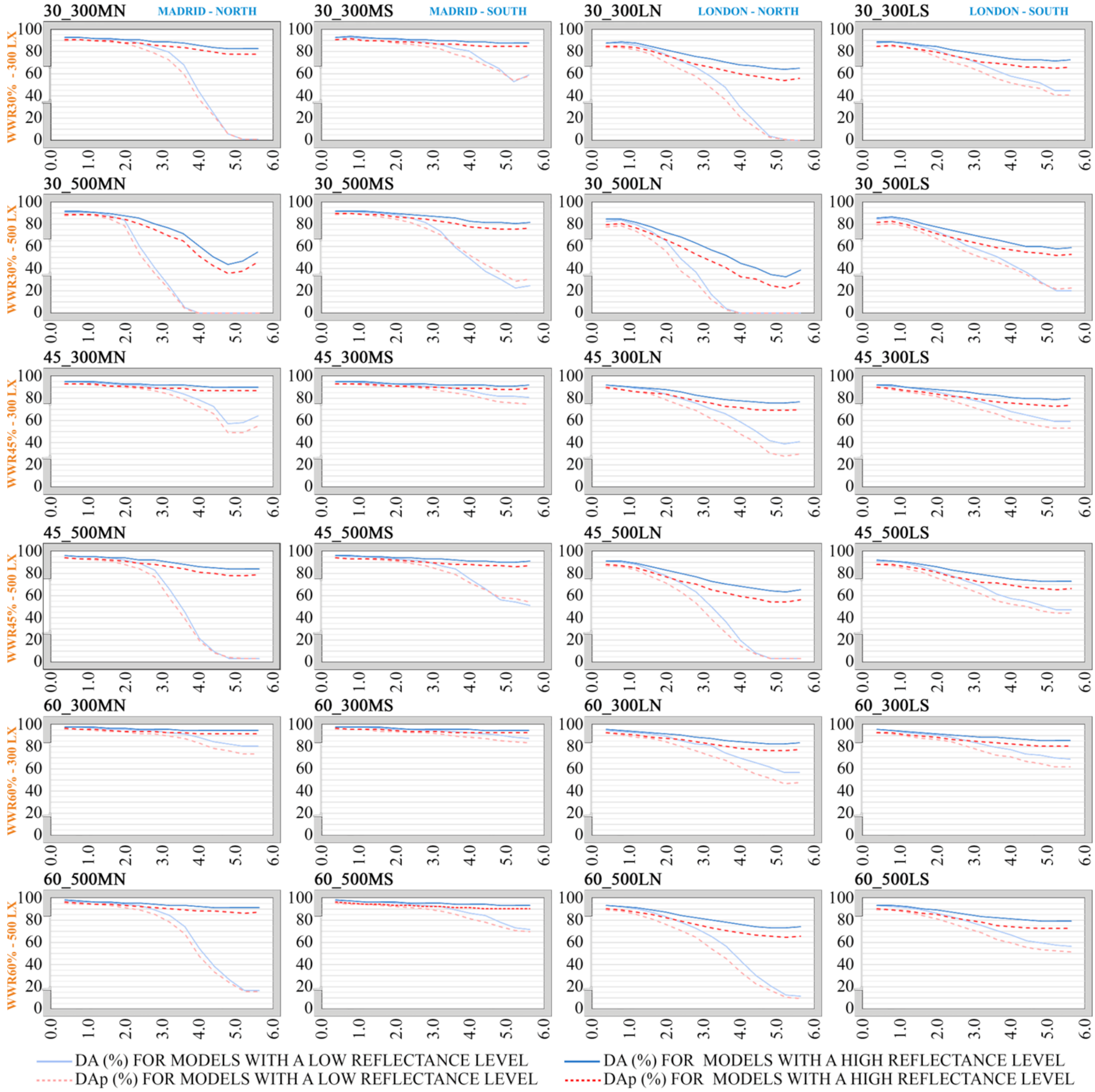

Figure 6. Quantification of DA and DAp in the calculation models according to room reflectance.

4.4. Divergence of DA and DAp According to Room Location

The last analysis quantifies the divergence of DA and DAp according to the different climate conditions of the room location: London UK, with mainly overcast skies and Madrid, Spain, with predominantly clear skies. It could be assumed that the differences of the climate conditions will affect to the use of daylight during the summer season, where DAp is ignoring most of the days in its calculation process. Figure 7 shows the results for both metrics according to the room location. As in the previous trials, the first and second rows show the room sections with a window-to-wall ratio of 30%, third and fourth rows show medium-size openings with a relative surface of 45% and the last two rows describe the results for large windows which correspond to a ratio of 60%. Odd columns represent bright rooms, with inner surfaces with a high reflectance value, while even columns show dark rooms. In addition, odd rows describe the results for an illuminance threshold of 300 lx, while even rows show the quantification of the metrics for the upper requirement of 500 lx. Finally, the left columns describe the results for windows facing North, while right columns represent the opposite orientation. As in previous studies, labels located in the left-top of the room sections describe the calculation model in accordance with parameters defined in Table 2.

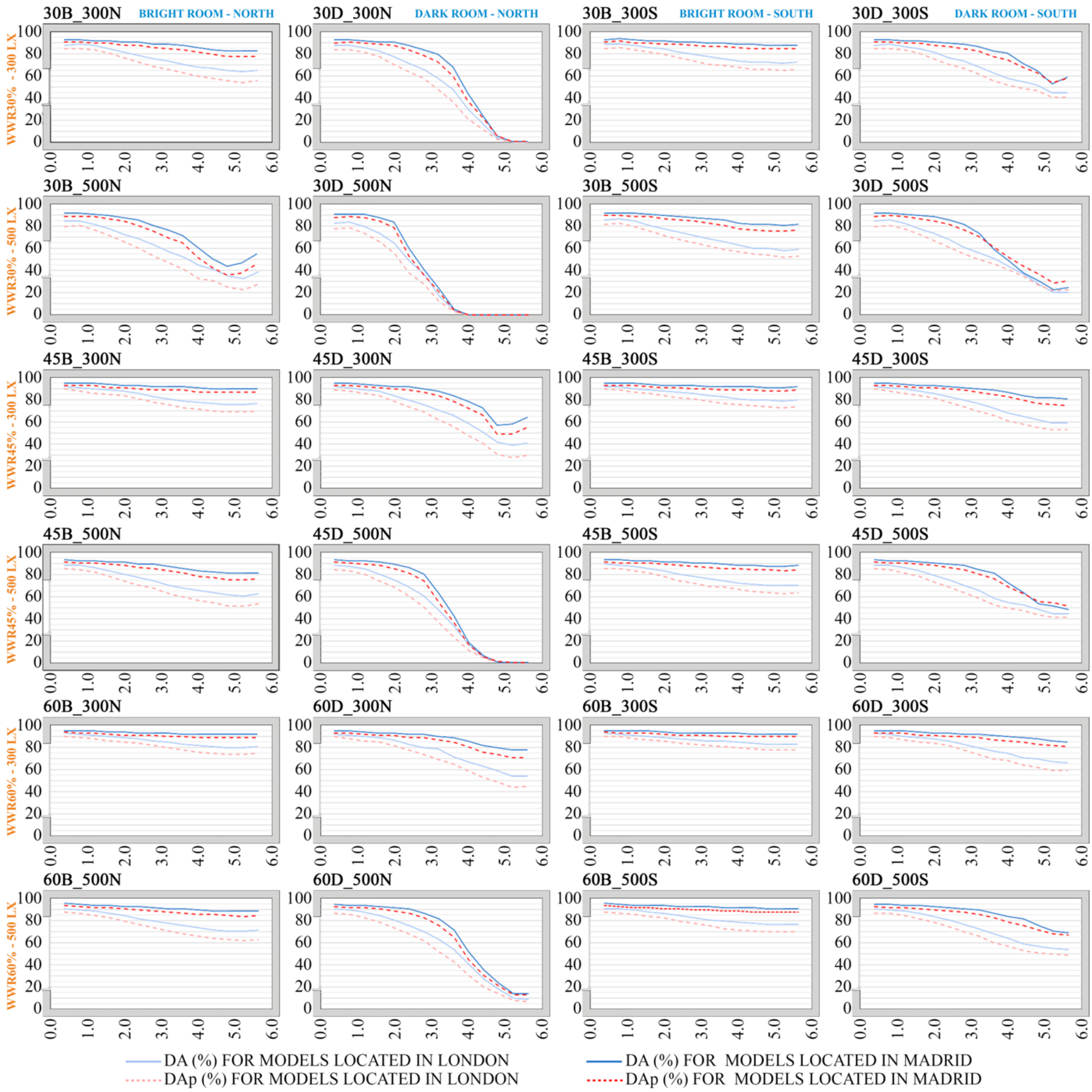

Figure 7. Quantification of DA and DAp in the calculation models according to room location.

As deduced from Figure 7, study cases located in Madrid with an illuminance requirement of 300 lx show a not significant difference between DA and DAp, due to the fact that both metrics achieve very high values, mainly with medium-size or large windows. Quantifying this assertion, it can be observed that the mean deviation for Madrid location, with mainly clear skies, is 3.8%, with a standard deviation of 1.3%. These values slightly increase for a threshold of 500 lx, where the mean deviation goes up to 5.6%, keeping a standard deviation of 2.9%. Therefore, it can be deduced that the difference between DA and DAp is almost negligible for locations with a predominance of clear skies and rooms with sufficient access to daylight.

The opposite case occurs for the London scenario. The divergence of both studied metrics increases considering a location with predominantly overcast skies and therefore poorer access to daylight. As deduced from Figure 7, the mean deviation between DA_{300} and $DAp_{300[243–182]}$ is 9.4%, with a standard deviation of 4.0%. This divergence is higher for the study cases with a higher illuminance threshold. According to a lighting requirement of 500 lx, the mean deviation increases up to 12.6%. Therefore, the application of DAp allows for more accurate results, especially for those locations with mainly overcast skies.

5. Discussion

According to the previous analysis of results, the divergence between DA and DAp based on windows size increases in an almost constant way when the illuminance threshold is higher or when the access to natural light is poorer, showing the maximum difference in the back of the room. In addition, when window orientation is analyzed, North models show a greater divergence between both metrics than those to the South, especially in the aforementioned area close to the back of the room.

The reflectance of the inner surfaces, considering usual values like those described in this study, did not act as a decisive parameter to determine the difference between both metrics, given that DAp showed lower mean deviations in comparison with DA. Finally, the DAp metric was more accurate for those locations with mainly overcast skies, e.g., London, than for those with mainly clear skies.

As a result, it can be stated that the real autonomy of daylight for seasonal use spaces with summer vacations is lower than that obtained by the classical metric of DA, especially when there is a poorer access to daylight. Thus, the access to daylight determines the divergence between DA and DAp. The limited access to natural light in an indoor space depends on a combination of two or more architectural parameters, such as the predominance of overcast skies, windows facing a northern orientation, or small openings, as well as, although to a lesser extent, the reflectance of the inner surfaces.

In this way, this new metric allows a more precise characterization of the access to daylight in seasonal use spaces, and, by definition, of the energy consumption of electric lighting. A mean divergence of 8–12% between DA and DAp implies a real energy consumption of electric lighting of 8–12% more than that estimated with DA, which can be translated to a certain unforeseen actual energy consumption depending on the lighting efficiency and the illuminance requirements. It is also worth stressing that the present study was performed using a classroom as a case study, but the DAp metric can be useful not only for educational buildings, but also for other seasonal spaces, such as hotels for summer or high mountain vacation periods, hospital rooms closed during summer holidays, or study rooms and libraries out of exam periods, among others.

6. Conclusions

The present paper proposes a new dynamic daylight metric for seasonal use spaces, namely partial daylight autonomy (Dap), as an adaptation of the existing daylight autonomy metric. This new metric allows to quantify with greater precision the energy savings achieved by a rational use of electric lighting in seasonal use spaces such as educational buildings.

A multipurpose classroom is taken as an example of methodological application of the DAp metric in spaces of seasonal use, in which the higher performance of daylight during summer should be ignored. Thus, the real autonomy of daylight in this case of application is actually lower than that determined by the classical metric of DA, especially when there is a poorer access to daylight.

The analysis of the results was carried out considering a set of simulation hypotheses generated from the base case study. They were defined by combining three variable characteristics (windows-to-wall ratio, orientation, room reflectance) in two different locations (Madrid, with mainly clear sky conditions, and London, with mainly overcast sky conditions), using two illuminance thresholds (300 and 500 lx).

The divergence between the DA and DAp results according to windows size is noticeable, increasing in an almost constant way when the illuminance threshold is higher or when the access to natural light is poorer (a mean deviation of 7.5% with a 300 lx threshold and 10.6% for 500 lx, in the case of an opening size of 30%), and showing the maximum difference at the back of the room (a maximum divergence of 18.5% and 22%, respectively).

When the variable under study is the windows orientation, North models show a bigger divergence between both metrics than those to the South. This happens especially in the area close to the back of the room, given that DAp provides a more accurate approach to the real use of daylight in this seasonal use space when the access to natural light is poorer. The mean deviation for windows facing North is 8.0% with a threshold of 300 lx and 12.5% for 500 lx, while these values decrease when the window is facing South, with 5.2% and 5.6% respectively.

In the case of the comparison of the metrics according to the reflectance of the inner surfaces, DAp does not provide a noticeable deviation in comparison with DA (mean deviations of 5.1% for 300 lx and 8.1% for 500 lx). Thus, it is not a decisive parameter to determine the difference between both metrics.

Finally, the application of DAp shows more accurate results for those locations with mainly overcast skies such as London (mean deviations of 9.4% for 300 lx and 5.6% for 500 lx) than for those with mainly clear skies (3.8% and 2.9% respectively).

Given these conclusions, it can be stated that, in the case of educational buildings, the poorer the access to natural light (small windows, window facing North, or locations with mainly overcast skies), the higher the divergence produced between DAp and DA, reaching divergences in the results close to 10%. Thus, the use of this new metric allows for a more precise and adjusted characterization of the entry of daylight in seasonal use spaces, and therefore a more accurate estimate of the impact on energy consumption if an electric lighting control system is implemented through lux meters.

Author Contributions: Conceptualization, A.R., M.Á.C., I.A. and Ó.L.; methodology, A.R., M.Á.C., I.A. and Ó.L.; software, A.R., M.Á.C., I.A. and Ó.L.; validation, A.R., M.Á.C., I.A. and Ó.L.; formal analysis, A.R., M.Á.C., I.A. and Ó.L.; investigation, A.R., M.Á.C., I.A. and Ó.L.; resources, A.R., M.Á.C., I.A. and Ó.L.; data curation, A.R., M.Á.C., I.A. and Ó.L.; writing—original draft preparation, A.R., M.Á.C., I.A. and Ó.L.; writing—review and editing, A.R., M.Á.C., I.A. and Ó.L.; visualization, A.R., M.Á.C., I.A. and Ó.L.; supervision, A.R., M.Á.C., I.A. and Ó.L.; project administration, A.R., M.Á.C., I.A. and Ó.L.; funding acquisition, A.R., M.Á.C., I.A. and Ó.L. All authors have read and agreed to the published version of the manuscript.

Funding: The results presented were funded by the Ministry of Science and Innovation of the Government of Spain through the research projects DYNALIGHT: Efficient design for biodynamic lighting to promote the circadian rhythm in shift work centers (Ref BIA2017-86997-R) and CHRONOLIGHT: Biodynamic wide spectrum lighting for biological chronoregulation and pathogens neutralization in hospital facilities (Ref PID2020-117563RB-I00). The authors wish to express their thanks for all the technical and financial support provided, including the research project: CARELight_Lite: Biodynamic lighting for circadian rhythm regulation of healthcare personnel in Pediatric Intensive Care Units (Ref PI-0136-2019).

Acknowledgments: The authors are grateful to all those who collaborated in this research project, especially to Blas de Lezo for encouraging this article. The authors also wish to thank the Junta de Andalucía and the University of Seville for providing the test cell facilities which made it possible to validate the metrics used in this research.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Ryckaert, W.R.; Lootens, C.; Geldof, J.; Hanselaer, P. Criteria for energy efficient lighting in buildings. *Energy Build.* **2010**, *42*, 341–347. [CrossRef]
2. Lam, J.C.; Li, D.H.W.; Cheung, S.O. An analysis of electricity end-use in air-conditioned office buildings in Hong Kong. *Build. Environ.* **2003**, *38*, 493–498. [CrossRef]
3. Acosta, I.; Navarro, J.; Sendra, J.J.; Esquivias, P. Daylighting design with lightscoop skylights: Towards an optimization of proportion and spacing under overcast sky conditions. *Energy Build.* **2012**, *49*, 394–401. [CrossRef]
4. Acosta, I.; Navarro, J.; Sendra, J.J. Towards an analysis of the performance of lightwell skylights under overcast sky conditions. *Energy Build.* **2013**, *64*, 10–16. [CrossRef]
5. Haq, M.A.U.; Hassan, M.Y.; Abdullah, H.; Rahman, H.A.; Abdullah, M.P.; Hussin, F.; Said, D.M. A review on lighting control technologies in commercial buildings, their performance and affecting factors. *Renew. Sustain. Energy Rev.* **2014**, *33*, 268–279. [CrossRef]
6. Bellia, L.; Fragliasso, F. New parameters to evaluate the capability of a daylight-linked control system in complementing daylight. *Build. Environ.* **2017**, *123*, 223–242. [CrossRef]
7. Wagiman, K.R.; Abdullah, M.N.; Hassan, M.Y.; Mohammad Radzi, N.H.; Abu Bakar, A.H.; Kwang, T.C. Lighting system control techniques in commercial buildings: Current trends and future directions. *J. Build. Eng.* **2020**, *31*, 101342. [CrossRef]
8. Acosta, I.; Campano, M.A.; Domínguez, S.; Fernández-Agüera, J. Minimum Daylight Autonomy: A New Concept to Link Daylight Dynamic Metrics with Daylight Factors. *LEUKOS-J. Illum. Eng. Soc. N. Am.* **2019**, *15*, 251–269. [CrossRef]
9. Leslie, R.P.; Radetsky, L.C.; Smith, A.M. Conceptual design metrics for daylighting. *Light. Res. Technol.* **2012**, *44*, 277–290. [CrossRef]
10. Esquivias, P.M.; Munoz, C.M.; Acosta, I.; Moreno, D.; Navarro, J. Climate-based daylight analysis of fixed shading devices in an open-plan office. *Light. Res. Technol.* **2016**, *48*, 205–220. [CrossRef]
11. Acosta, I.; Campano, M.A.; Molina, J.F. Analysis of energy savings and visual comfort produced by the proper use of windows. *Int. J. Eng. Technol.* **2016**, *8*, 358–365. [CrossRef]
12. Commission Internationale de l'Éclairage. *International Lighting Vocabulary-CIE S 017:2011*; Commission Internationale de l'Éclairage: Vienna, Austria, 2011.
13. Commission Internationale de l'Éclairage. *Spatial Distribution of Daylight-CIE Standard General Sky-CIE S 011/E: 2003*; Commission Internationale de l'Éclairage: Vienna, Austria, 2003.
14. Cheng, V.; Steemers, K.; Montavon, M.; Compagnon, R. Compact cities in a sustainable manner. In Proceedings of the 2nd International Solar Cities Congress, Oxford, UK, 3–6 April 2006; pp. 1–11.
15. Acosta, I.; Varela, C.; Molina, J.F.; Navarro, J.; Sendra, J.J. Energy efficiency and lighting design in courtyards and atriums: A predictive method for daylight factors. *Appl. Energy* **2018**, *211*, 1216–1228. [CrossRef]
16. Boyce, P.R. The impact of light in buildings on human health. *Indoor Built Environ.* **2010**, *19*, 8–20. [CrossRef]
17. Association Suisse des Electriciens. *Éclairage intérieur par la lumière du jour-Swiss Norm SN 418911*; Association Suisse des Electriciens: Lucerne, Switzerland, 1989.
18. Reinhart, C.F.; Mardaljevic, J.; Rogers, Z. Dynamic Daylight Performance Metrics for Sustainable Building Design. *LEUKOS-J. Illum. Eng. Soc. N. Am.* **2006**, *3*, 7–31. [CrossRef]
19. Rakha, T.; Chen, Y.; Reinhart, C. Do office buildings 'save' energy in the United States due to Daylight Saving Time (DST)? A 50-State simulation-based study. In Proceedings of the 2018 Building Performance Analysis Conference and SimBuild co-organized by ASHRAE and IBPSA-USA, Chicago, IL, USA, 26–28 September 2018; pp. 21–28.
20. Mardaljevic, J.; Brembilla, E.; DrosouSchool, N. Real-World Validation of Climate-Based Daylight Metrics: Mission Impossible? In *CIBSE Technical Symposium*; Loughborough University: Loughborough, UK, 2016; pp. 1–12.
21. Campano, M.A.; Acosta, I.; León, A.L.; Calama, C. Validation Study for Daylight Dynamic Metrics by Using Test Cells in Mediterranean Area. *Int. J. Eng. Technol.* **2018**, *10*, 487–491. [CrossRef]
22. Acosta, I.; Campano, M.Á.; Leslie, R.; Radetsky, L. Daylighting design for healthy environments: Analysis of educational spaces for optimal circadian stimulus. *Sol. Energy* **2019**, *193*, 584–596. [CrossRef]
23. Galatioto, A.; Beccali, M. Aspects and issues of daylighting assessment: A review study. *Renew. Sustain. Energy Rev.* **2016**, *66*, 852–860. [CrossRef]
24. Acosta, I.; Campano, M.Á.; Domínguez-Amarillo, S.; Muñoz, C. Dynamic Daylight Metrics for Electricity Savings in Offices: Window Size and Climate Smart Lighting Management. *Energies* **2018**, *11*, 3143. [CrossRef]
25. Nabil, A.; Mardaljevic, J. Useful daylight illuminance: A new paradigm for assessing daylight in buildings. *Light. Res. Technol.* **2005**, *37*, 41–57. [CrossRef]
26. Nabil, A.; Mardaljevic, J. Useful daylight illuminances: A replacement for daylight factors. *Energy Build.* **2006**, *38*, 905–913. [CrossRef]
27. IESNA. *IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)*; IESNA: New York, NY, USA, 2013.
28. Bellia, L.; Pedace, A.; Barbato, G. Winter and summer analysis of daylight characteristics in offices. *Build. Environ.* **2014**, *81*, 150–161. [CrossRef]
29. León-Rodríguez, Á.L.; Suárez, R.; Bustamante, P.; Campano, M.Á.; Moreno-Rangel, D. Design and Performance of Test Cells as an Energy Evaluation Model of Facades in a Mediterranean Building Area. *Energies* **2017**, *10*, 1816. [CrossRef]

30. Tregenza, P.R.; Waters, I.M. Daylight coefficients. *Light. Res. Technol.* **1983**, *15*, 65–71. [CrossRef]
31. Mardaljevic, J. Simulation of annual daylighting profiles for internal illuminance. *Int. J. Light. Res. Technol.* **2000**, *32*, 111–118. [CrossRef]
32. Perez, R.; Seals, R.; Michalsky, J. All-weather model for sky luminance distribution-Preliminary configuration and validation. *Sol. Energy* **1993**, *50*, 235–245. [CrossRef]
33. Reinhart, C.F.; Walkenhorst, O. Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. *Energy Build.* **2001**, *33*, 683–697. [CrossRef]
34. Acosta, I.; Muñoz, C.; Esquivias, P.; Moreno, D.; Navarro, J. Analysis of the accuracy of the sky component calculation in daylighting simulation programs. *Sol. Energy* **2015**, *119*, 54–67. [CrossRef]
35. Mohsenin, M.; Hu, J. Assessing daylight performance in atrium buildings by using Climate Based Daylight Modeling. *Sol. Energy* **2015**, *119*, 553–560. [CrossRef]
36. Crone, S. Radiance Users Manual Vol. 2. Lawrence Berkeley Laboratory: Berkeley, CA, USA, 1992.
37. Mardaljevic, J. *Daylight Simulation: Validation, Sky Models and Daylight Coefficients*; Loughborough University: Loughborough, UK, 2000.
38. Bellia, L.; Acosta, I.; Campano, M.Á.; Fragliasso, F. Impact of daylight saving time on lighting energy consumption and on the biological clock for occupants in office buildings. *Sol. Energy* **2020**, *211*, 1347–1364. [CrossRef]
39. de Andalucía, J. Orden de 24 de enero de 2003 de la Consejería de Educación y Ciencia de la Junta de Andalucía por la que se aprueban las "Normas de diseño y constructivas para los edificios de uso docente". *Boletín Of. La Junta Andal.* **2003**, *43*, 4669.
40. Campano, M.A. Confort térmico y eficiencia energética en espacios con alta carga interna climatizados: Aplicación a espacios docentes no universitarios en Andalucía. Ph.D. Thesis, Universidad de Sevilla, Seville, Spain, 2015.
41. CEN-European Committee for Standardization. *EN 12464-1:2002-Light and Lighting-Lighting of Work Places-Part 1: Indoor Work Places*; CEN-European Committee for Standardization: Brussels, Belgium, 2012.
42. LBNL. *Lawrence Berkeley National Laboratory Technical Report (2012) 1278-EnergyPlus Engineering Reference*; The Reference to EnergyPlus Calculations: Berkeley, CA, USA, 2012.
43. Association Suisse des Electriciens. *Spatial Distribution of Daylight-Luminance Distributions of Various Reference Skies-CIE 110-1994*; Association Suisse des Electriciens: Lucerne, Switzerland, 1994.
44. Munoz, C.M.; Esquivias, P.M.; Moreno, D.; Acosta, I.; Navarro, J. Climate-based daylighting analysis for the effects of location, orientation and obstruction. *Light. Res. Technol.* **2014**, *46*, 268–280. [CrossRef]