Analysis and Results Derived from the Development of the Dynamic Metric "Partial Daylight Autonomy (DAp)" for Seasonal Spaces: Application to Non-University Classrooms

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Abstract—**This work proposes a development of the results and a further analysis about the *Partial Daylight Autonomy* (DAp) dynamic metric for daylighting, based on the Daylight Autonomy (DA), that allows a more accurate natural lighting study for any seasonal use space. In that way, an optimization of window gaps in facade and more efficient lighting levels related to the real necessities of the space could be reached. Thus, all the concepts and previous studies about this metric are supported by a mathematical basis and also applied to a non-university classroom.**

Index Terms—**dynamic metric, partial daylight autonomy, seasonal use buildings, energy efficiency, daylighting, architecture and health**

I. Introduction

Nowadays, society is becoming aware of the impact of energy consumption on buildings. Electric lighting is one of the main facilities of a building and it represents a noticeable impact on the total energy consumption. Given this context, the daylight dynamic metrics, are useful tools to save energy according to a suitable window design and a proper use of daylighting.

Given the health context, disassociating our activities from daylight carried some health problems among humans, increasing the risk of developing some diseases [1], [2].

Moreover, in the current context with the 20/20/20 Horizon in sight and global awareness about the importance of optimizing the use of energy, it is necessary to reach an efficient method for designing the size of the windows in order to take advantage of daylight, for which Dynamic Daylight metrics [3], [4] can be used.

In Spain, 20% of the electricity consumption is made by buildings [5], being 28% of it due to electric lighting, so that making predictive computational models analysed with dynamic metrics can mean a decrease on the electricity consumption [6], both due to the windows size optimization [7], [8] and to the use of a smart control of the architectural spaces [9], [10].

Nevertheless, there is a casuistry that dynamic metrics do not consider as many buildings have a temporary use throughout the year, for example educational centres that have no use along the summer period. This type of building is highly widespread throughout Andalusia, where there are more than 7000 public schools, so saving part of the energy consumed by electric lighting systems of these schools can result in large-scale energy savings.

II. Objectives

The aim of this work is to develop a deeper research on the potential of a new lighting dynamic metric, the Partial Daylight Autonomy (DAp) [11], based on the widely known Daylight Autonomy (DA) metric [4], which determines the percentage of the occupancy time during which an illuminance threshold is met by daylight alone. Thus, it would be possible to consider the non-use periods of a space and so not oversizing nor the penetration or amount of natural light that comes through its windows [12], allowing to fit window gaps size to the real conditions and necessities of the room. So as to verify the impact of this metric, it has been applied to a case study based on a secondary school multipurpose classroom, defined in the previous article [11], in order to check its behaviour considering some concrete guidelines explained in the methodology, based on a mathematical and a comprehensive analysis of results.

III. Methodology

A. Case Study Definition

The case study was defined in the previous paper [11], based on previous works of Acosta et al. [13] and Campano et al. [14], [15], [16], [17], [18], [19], which refers to a conventional secondary school multipurpose classroom with a width of 8 meters, a depth of 6 metres and a height of 3 metres, having a window gap size of 7x1 metres (30% of the vertical plane) oriented north and

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centred in the facade (Fig. 1). The photometric conditions of the materials for this study are defined in Table I.

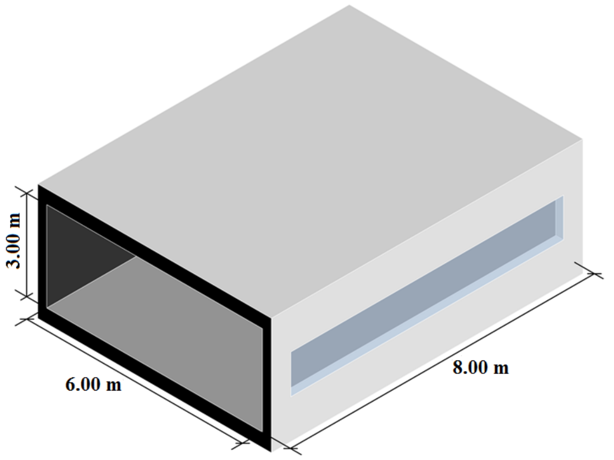

Figure 1. Study case of a standard secondary classroom.

TABLE I. PHOTOMETRIC CONDITIONS OF THE MATERIALS OF THE STUDY CASE [19]

	Ceiling	Floor	Walls	Window
Reflectance	0.80	0.60	0.80	-
Reflection	1.00	1.00	1.00	1.00
Optical Transmittance	0.00	0.00	0.00	0.75

The model has been located in Madrid (Spain), with a standard academic year (not considering weekends) and an uninterrupted schedule from 8:30 – 18:30 (including DST); all that considering the recommended illuminance of 500 lux [20].

The calculation grid is placed 60 cm above the floor, with a distance between calculation points of 30x30 cm. The results are obtained from the middle section of the facade.

B. *Calculation Tools Selection*

The selected tool for developing the simulations is DIVA 4.0, a dynamic lighting calculating software (developed by the MIT) based on the Radiance calculation engine created by C. Reinhart. This program works with the *daylight coefficients* defined by Mardaljevic [21] and has been validated by the international scientific community.

Rhinoceros 5.0 has been used to create the 3D model, as it is the interface that supports DIVA. Table II shows the calculation parameters used in DIVA for this study.

TABLE II. PARAMETERS OF CALCULATION

Parameter	Value	Parameter	Value
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		

C. *Calculation Tool Validation*

The validation process of the calculation tool is similar to that proposed in previous publications [11] by comparison with a real model based on a test cell [22] that was monitored for a full year (Fig. 2).

Figure 2. Test cells [22].

For this validation, the calculation database and experimental results are based on the previous publication of Campano et al. [23] using the mentioned test cell.

The cell is located in Seville (Spain) and is characterised by the dimensions of 2.40 meters wide, 3.20 meters deep and 2.70 meters high, with a window of 1.16x1.08 m (corresponding to 20% of the vertical plane) centred on the facade and facing south and also considering the factors described in Table III.

TABLE III. PHOTOMETRIC CONDITIONS OF THE STUDY CASE MATERIALS [23]

	Ceiling	Floor	Walls	Window
Reflectance	0.72	0.22	0.72	-
Solar factor	-	-	-	0.75
Conservation factor	-	-	-	0.80

The 3D model is generated with Rhinoceros and subsequently calculated using DIVA, thus obtaining the DA values for an uninterrupted schedule from 08:00 to 17:00 (including DST) and two different thresholds of illuminance of 100 and 500 lx. Afterwards, a comparison is made between the previous values obtained, both measured and computer-calculated with Daysim [23], which are those obtained in the present study with DIVA.

The maximum divergence among the values is lower than 10% in the worst case, as shown in Fig. 3, so the validation of the tool is statistically correct.

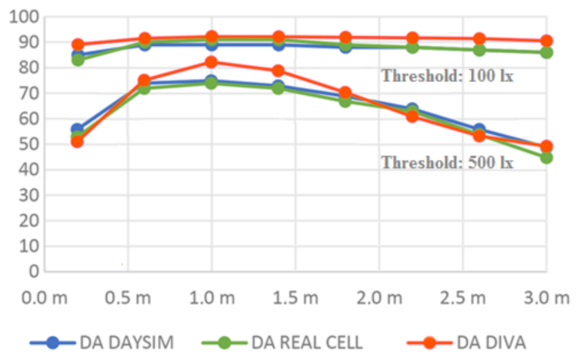

Figure 3. Test Cell DA values for 100 lx and 500 lx illuminance thresholds.

D. Calculation Variables Validation.

To develop this study, several variables have been considered and so generating the following cases grouped into the next two sets.

The first group refers to physical variables such as window size (Table IV) and the reflectance of the materials (Table V).

TABLE IV. WINDOW GAP SIZE VARIABLES SET

Window to façade relation	Length (m)	Height (m)	Surface (m)
30	7.00	1.00	7.00
60	7.00	2.00	14.00

TABLE V. INTERIOR MATERIALS REFLECTANCE VARIABLES SET

Model materials set	Reflectance			Glass visible transmittance
	Ceiling	Floor	Walls	
Bright	0.80	0.80	0.60	0.75
Dark	0.60	0.20	0.40	0.75

The second set deals with the variables of the model, such as the window orientation (north and south).

All variables are combined as can be seen in Table VI.

TABLE VI. HYPOTHESES OF CALCULATION

Model	Windows to facade (%)	Reflectance			Glass visible transm.	Location	Orient.
		Ceiling	Floor	Walls			
30CB_MN	30	0.80	0.50	0.80	0.75	Madrid	North
30CD_MN	30	0.60	0.20	0.40	0.75	Madrid	North
45CB_MN	45	0.80	0.50	0.80	0.75	Madrid	North
45CD_MN	45	0.60	0.20	0.40	0.75	Madrid	North
60CB_MN	60	0.80	0.50	0.80	0.75	Madrid	North
60CD_MN	60	0.60	0.20	0.40	0.75	Madrid	North
30CB_MS	30	0.80	0.50	0.80	0.75	Madrid	South
30CD_MS	30	0.60	0.20	0.40	0.75	Madrid	South
45CB_MS	45	0.80	0.50	0.80	0.75	Madrid	South
45CD_MS	45	0.60	0.20	0.40	0.75	Madrid	South
60CB_MS	60	0.80	0.50	0.80	0.75	Madrid	South
60CD_MS	60	0.60	0.20	0.40	0.75	Madrid	South

Lastly, these cases are studied with seasonal occupation schedules, simulating the full standard year without holidays for the calculation of Daylight Autonomy (DA) and, on the other hand, the same year without occupation during July and August for the calculation of Partial Daylight Autonomy (DAp), according to the Spanish summer vacation period. Due to this, the metric is expressed as DAp [500lx, 255-165], in reference to the illuminance threshold (500 lux) and an annual period of measurement, represented as an interval in days of the year.

E. Results Analysis Tools Definition.

The results obtained from the simulation process have been analysed in two different ways.

On the one hand, a graphic analysis has been carried out, studying the pattern of each graphic to group them according to their behaviour.

On the other hand, a deviation analysis has been made, taking into account the mean and standard deviation of the calculation model with the aim of understanding how each model behaves and what is the numerical impact of the use of DA against the use of DAp [500lx, 255-165].

IV. CALCULATING AND ANALYSIS OF RESULTS

A. Results and Deviations

Each casuistry, the ones in the Table VI (a total of 8), has been studied with DIVA twice, one considering all-year occupation, so obtaining DA, and another taking into account the non-use periods, so obtaining DAp. Those results have been compared between them so that the difference of considering summer holidays or not in the lighting study has been noticeable.

As referred in the previous paper [11], graphics could be studied into four behaviour groups:

In Group A it is possible to find decreasing curves (DA is higher than DAp) as they get away from the window, yet never crossing or reaching the value of zero. All the models with a *bright* reflectance level can be found in this group. A clear results example of that is the graphic of the model "30CB_MN" (Fig. 4):

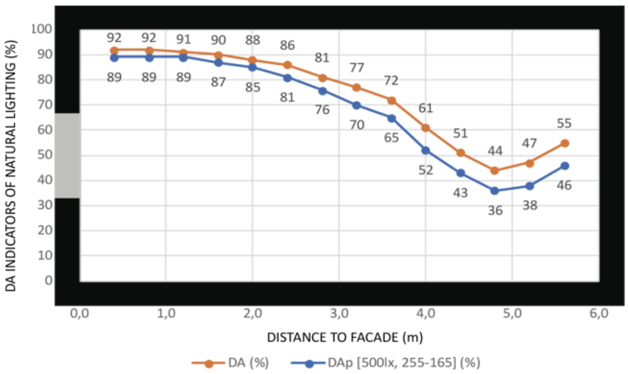

Figure 4. Model 30CB_MN results graphic.

Considering the values of DA and DAp (represented in the graphic), it has been calculated the deviance for every calculation node as it can be seen in Table VII:

TABLE VII. 30CB_MN: CALCULATING NODES DEVIATIONS

Model Depth (m)	DA (%)	DAp [500lx, 255-165] (%)	DEVIATION (%)
0.40	92	89	3
0.80	92	89	3
1.20	91	89	2
1.60	90	87	3
2.00	88	85	4
2.40	86	81	6
2.80	81	76	7
3.20	77	70	10

Model Depth (m)	DA (%)	DAp [500lx, 255-165] (%)	DEVIATION (%)
3.60	72	65	11
4.00	61	52	17
4.40	51	43	19
4.80	44	36	22
5.20	47	38	24
5.60	55	46	20

It is worth noting that a shorter interval of days will give a higher divergence between DA and DAp. Furthermore, those specific deviations have been taken in order to develop a proper deviance analysis obtaining a mean deviation and a standard deviation, shown in Table VIII:

TABLE VIII. 30CB_ MN: MEAN AND STANDARD DEVIATIONS

Model	Mean Deviation (%)	Standard Deviation (%)
30CB_MN	11	8

This process has been developed for every model variation, so that the mean and standard deviations of each case study shift (which can be found in graphics Group A) are shown in Table IX:

TABLE IX. GROUP A: MEAN AND STANDARD DEVIATIONS

Model	Mean Deviation (%)	Standard Deviation (%)
30CB_MN	11	8
45CB_MN	5	2
60CB_MN	4	1
30CB_MS	5	2
45CB_MS	4	1
60CB_MS	3	1

In Group B it can be found graphics which, though following the same behaviour as those in Group A, the zero value is reached as getting closer to the room fund; the majority of *dark* reflectance level models are found in this group. An example of the results for that group is the graphic of the model "30CD_MN" (Fig. 5):

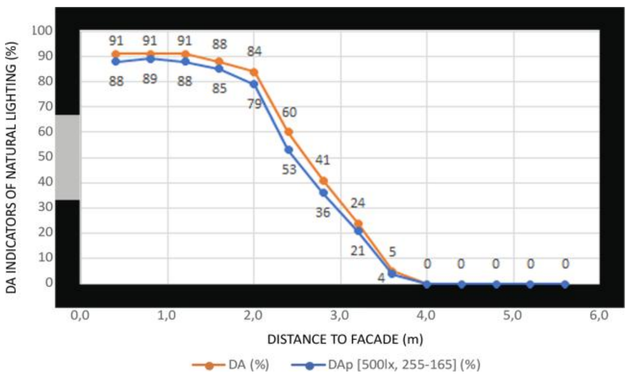

Figure 5. Model 30CD_MN results graphic.

Following the method defined for Group A, they have been obtained the mean and standard deviations for every graphic contained in Group B as can be seen in Table X:

TABLE X. GROUP B: MEAN AND STANDARD DEVIATIONS

Model	Mean Deviation (%)	Standard Deviation (%)
30CD_MN	9	8
45CD_MN	9	6
60CD_MN	8	6

In Group C it is possible to find graphics with a beginning similar from the previous groups, but as they keep warding off the fa çade, there is a crossing point of the curves so that DAp is higher than DA from that point to the background; a reason for that is associated with the elevation angle of the sun in winter (compared to the one in summer), reaching a deeper penetration level to the background of the room and obtaining so higher illumination levels. A *dark* reflectance level and south orientation are the main characteristics for these graphics. Besides, due to that values line cross, it is possible to perceive the non-lineal correlation between DA ad Dap in many of the cases. An example of the results for that group is the graphic of the model "30CD_MS" (Fig. 6):

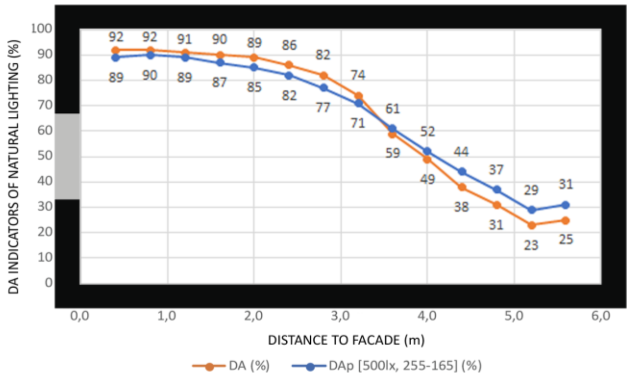

Figure 6. Model 30CD_MS results graphic.

Following the method defined for the previous groups, they have been obtained the mean and standard deviations for every graphic contained in Group C as can be seen in Table XI:

TABLE XI. GROUP C: MEAN AND STANDARD DEVIATIONS

Model	Mean Deviation (%)	Standard Deviation (%)
30CD_MS	3	10
45CD_MS	2	4

In Group D they can be found graphic that follow the same pattern as those in Group A, although the values divergence is noticed to be decreasing as they get to the room fund, tending to cross. If the depth of the case study room was higher, the behaviour of this graphic would be as those in Group C, showing the cross of DA and DAp curves. An example of the results for that group is the graphic of the model "60CD_MS" (Fig. 7):

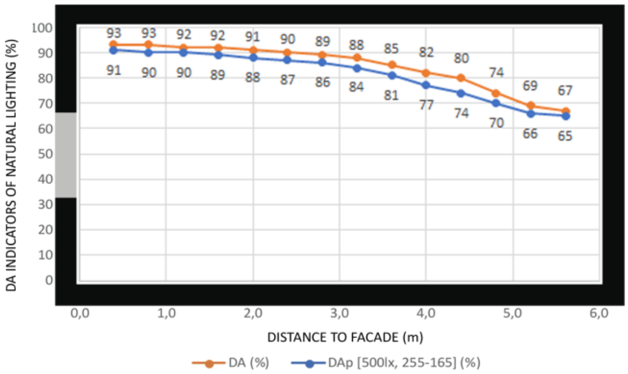

Figure 7. Model 60CD_MS results graphic.

Following the method defined for the previous groups, they have been obtained the mean and standard deviations for every graphic contained in Group D as can be seen in Table XII:

TABLE XII. GROUP D: MEAN AND STANDARD DEVIATIONS

Model	Mean Deviation (%)	Standard Deviation (%)
60CD_MS	4	2

B. Deviations Analysis

Considering all the graphics and its divergences, it has been developed a deviation analysis with the mean and the standard deviations specified previously. In order to be able to discretise what variables have a higher impact in the use or not-use of DAp, they have been grouped considering the variables:

Orientation

As it is shown in Table XIII, the deviations regarded to orientation are remarkable given that those one in models facing north are higher, so it is possible to qualify the better efficiency of DAp for north orientations rather than for south ones.

TABLE XIII. ORIENTATION DEVIATION ANALYSIS

Model	North		Model	South	
	Mean Dev.	Stand. Dev.		Mean Dev.	Stand. Dev.
30CB_MN	11	8	30CB_MS	5	2
45CB_MN	5	2	45CB_MS	4	1
60CB_MN	4	1	60CB_MS	3	1
30CD_MN	9	8	30CD_MS	3	10
45CD_MN	9	6	45CD_MS	2	4
60CD_MN	8	6	60CD_MS	4	2
	Mean Dev.	Stand. Dev.		Mean Dev.	Stand. Dev.
Mean Dev.	7.67	5.17	Mean Dev.	3.50	3.33
Stand Dev.	2.66	-	Stand Dev.	1.05	-

Reflectance

According to Table XIV, both variables deviations are found in the same range of divergence so that it is possible to affirm that DAp would mean an improvement whether the materials of the space have a high or low reflectance.

TABLE XIV. REFLECTANCE DEVIATION ANALYSIS

Model	Bright		Model	Dark	
	Mean Dev.	Stand. Dev.		Mean Dev.	Stand. Dev.
30CB_MN	11	8	30CD_MN	9	8
45CB_MN	5	2	45CD_MN	9	6
60CB_MN	4	1	60CD_MN	8	6
30CB_MS	5	2	30CD_MS	3	10
45CB_MS	4	1	45CD_MS	2	4
60CB_MS	3	1	60CD_MS	4	2
	Mean Dev.	Stand. Dev.		Mean Dev.	Stand. Dev.
Mean Dev.	5.33	2.50	Mean Dev.	5.83	6.00
Stand Dev.	2.88	-	Stand Dev.	3.19	-

Window size

As it is shown in Tables XV, XVI and XVII, the deviations of each window size are similar, and so efficient independent of it, yet it can be appreciated a light higher deviation for models with a 30% window size rather than those with a 45% or 60%.

TABLE XV. 30% WINDOW SIZE DEVIATION ANALYSIS

Model	30% Window Size	
	Mean Dev.	Stand. Dev.
30CB_MN	11	8
30CD_MN	9	8
30CB_MS	5	2
30CD_MS	3	10
	Mean Dev.	Stand. Dev.
Mean Dev.	7.00	7.00
Stand Dev.	3.65	-

TABLE XVI. 45% WINDOW SIZE DEVIATION ANALYSIS

Model	45% Window Size	
	Mean Dev.	Stand. Dev.
45CB_MN	5	2
45CD_MN	9	6
45CB_MS	4	1
45CD_MS	2	4
	Mean Dev.	Stand. Dev.
Mean Dev.	5.00	3.25
Stand Dev.	2.94	-

TABLE XVII. 60% WINDOW SIZE DEVIATION ANALYSIS

Model	60% Window Size	
	Mean Dev.	Stand. Dev.
60CB_MN	4	1
60CD_MN	8	6
60CB_MS	3	1
60CD_MS	4	2
	Mean Dev.	Stand. Dev.
Mean Dev.	4.75	2.50
Stand Dev.	2.22	-

V. Conclusions

According to the results and deviation analysis of this example, the use of this new dynamic metric, Partial Daylight Autonomy (DAp), means better fit in the results of daylighting calculations for spaces characterised for a seasonal use. In accordance with the previous statement, the usually lower value of DAp means that a building with a seasonal use requires a higher energy consumption in electric lighting during its period of operation in comparison with a typical building, due to the fact that the summer daylighting is not considered into calculation. Quantifying the previous deduction, the autonomy of daylight can fall up to 24%, depending on the orientation, window size and study point.

Furthermore, according to the previous analysis, it can be noticed that a high level of exposure to diffuse radiation on the model means a better divergence between DA and DAp indicators, so that north-oriented models are the best example for the use of DAp metric. On the other hand, reflectance and window size do not play such a big role in this decision and the indicator efficiency of use.

Besides, the non-lineal correlation between DA and DAp metric has been demonstrated, meaning a huge importance on the use of this new dynamic metric that cannot be defined directly from DA.

To sum up, this research demonstrates the great importance of considering the non-use periods of a space in order to develop its lighting study, so that it becomes highly recommended the use of this new Partial Daylight Autonomy dynamic metric.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

All authors conducted the research; all authors analyzed the data; all authors wrote the paper; all authors had approved the final version.

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