Dynamic Daylight Indicator for Seasonal Spaces: Application to Non-university Classrooms

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***Abstract* — This research proposes a new dynamic metric for natural lighting, called *Partial Daylight Autonomy* (DAp), generated from another existing and widely used metric, *Daylight Autonomy* (DA), so as to permit a more accurate daylight study of any space with a characteristic seasonal use. In this way, it is possible to optimize the size of windows in facade to achieve an efficient illumination level and faithful to the real necessity, removing the divergence that DA generates when months with no occupation are considered in calculations. This methodology is applied on a case study based on a multipurpose classroom of a secondary school, as an example of building with seasonal use.**

***Index Terms* — dynamic metrics, partial daylight autonomy, seasonal use buildings, efficient illumination, natural illumination, architecture and health**

I. Introduction

Natural lighting has always played an important role in people's lives, given that human activities along History have been mainly developed during day-time while night-time has usually been used for resting. In this way, the discovery of electric lighting meant a real revolution as those activities could also be developed at night. However, apart from these advantages, there were also some problems, as some health-related issues emerged [1] [2]. That is due to the biological necessity of sleeping at night, expressed through the circadian rhythms [3], [4], that are really important issues in people's health, but even more for underage children who are physically developing [3].

Furthermore, when the current 20-20-20 horizon and all the widely globalised concern about energy saving are taken into account, it becomes essential the use of natural lighting in architectonical design through the use of Dynamic Daylight metrics [5], [6]. The rational use of this natural source by means of previous computational simulation can help to minimise the consumption due to electric lighting [7], both through windows size design [8], [9] and smart control design [10], [11]. This is especially true for Spain, where the 20% of the global consumption is for buildings [12] and, among that, the 28% is used in electric lighting.

However, these Dynamic Daylight metrics do not take into account the possibility of occupation discontinuities due to seasonal uses, as in the case of educational centers, which creates an inaccuracy in the calculation models. Indeed, just in Andalucia, there are around 7000 public schools, which is a clear reflection of the impact that improved electric lighting savings in schools would mean in a higher scale.

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II. Objectives

The main objective pursued by this study is the development of a new natural illumination metric, the Partial Daylight Autonomy (DAp), based on the widely used and known Daylight Autonomy (DA), but considering a better fit to the period of use of the building and so taking into account the real natural light penetration and not oversizing its amount [13]. Thus, windows design in facade would be done based in the real situation and necessities of the building.

In order to check the impact of the DAp, it has been applied to a non-university teaching classroom (case study) and tested its repercussion in lighting, according to a series of specific guidelines defined in the methodology.

III. Methodology

A. *Case Study Definition.*

The case study, taken from previous works of Acosta et al. [14] and Campano et al [15]–[19], is based on a standard non-university teaching school classroom with 8 metres wide, 6 metres deep and a height of 3 metres, with a window hollow of 7x1 metres (occupying 30% of the vertical plane) centred in the facade and north-oriented, as can be seen in Fig 1. The photometric factors considered for this study are defined in Table I.

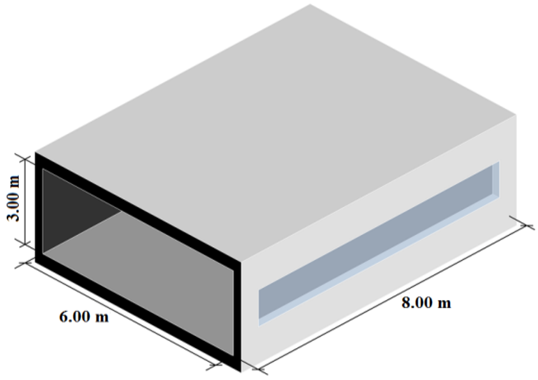

Figure 1. Standard non-university classroom under study.

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TABLE I. PHOTOMETRIC CONDITIONS OF THE MATERIALS OF THE STUDY CASE [20]

	Ceiling	Floor	Walls	Window
Reflectance	0.80	0.60	0.80	0.90
Reflection	1.00	1.00	1.00	1.00
Transmittance	0.00	0.00	0.00	0.75

A 30x30 cm grid of evaluating points is located over the floor (60 cm height). In order to develop the analysis, it has been considered the data obtained from the central section from the facade. The base model has been located in Madrid (Spain), considering a standard academic year (no weekends) with an uninterrupted schedule from 08:30 to 18:30 (including summer time: *Daylight Saving Time* or *DST*) and stablishing the recommended illuminance of 500 lux [21].

B. *Calculation Tools Selection.*

The tool selected for the development of this work is DIVA 4.0, which is a lighting calculating software created by the MIT and based on the Radiance (developed by C. Reinhart) calculation engine, which is widely endorsed by the scientific community and works with the *daylight coefficients* defined by Mardaljevic [22]. For proper operation, this tool uses Rhinoceros 5.0 as its 3D modelling interface. Among its options, it is worth highlighting its capacity of discretise the calculating process introducing the non-occupation periods of time along the year, which characterises seasonal use buildings.

Table II shows the calculation parameters used by this programme in 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 calculating tool was previously performed through comparison with a real model based on a test cell [23] which was monitored during a whole year (Fig. 2).

Figure 2. Test cells [23]

The calculation data base and experimental results for comparison were obtained from previous work of Campano et al. [24] using the aforementioned test cell.

This cell is located in Seville (Spain) with 2.40 metres width, 3,20 metres deep and a height of 2.70 metres, with an opening of 1.16x1.08 m (occupying 20% of the vertical plane) centred in the facade and south-oriented, as well as considering the factors in Table III.

TABLE III. PHOTOMETRIC CONDITIONS OF THE STUDY CASE MATERIALS [24]

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

A grid of points of 40x40 cm is located over the interior floor (6 cm height). In order to develop the analysis, it has been considered the data obtained from the central section from the facade. The model considers a standard whole year with an uninterrupted schedule from 08:00 to 17:00 (including summer time: *Daylight Saving Time* or *DST*) and taking into account two thresholds of illuminance of 100 and 500 lux.

According to the previous defined test cell model, it has been developed the same model with Rhinoceros and lately calculated with DIVA to get the Daylight Autonomy values. Then, considering the real values and the computational data obtained from the article (calculated with Daysim), it has been made a comparison in order to check the veracity of the calculating tool DIVA.

As can be seen in Fig 3, the maximum divergence among the values are really small and lower than a 10%, so the validation of the tool is statistically correct.

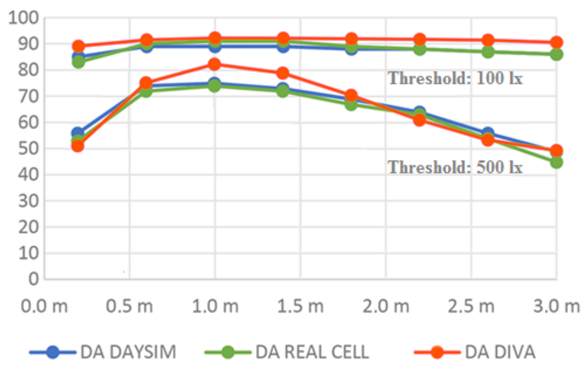

Figure 3. Test Cell DA values for 100lx and 500 lx illuminance thresholds

D. *Case Study Validation*

According to the previous defined case study, it has been developed the same model with Rhinoceros and lately calculated with DIVA to get the Daylight Autonomy values. Then, considering the computational values obtained from the article (calculated with Daysim), it has been made a comparison in order to check the similarity of the case study model developed.

As can be seen in Fig 4, the maximum divergence between the values is about 10%, so the validation of the model is statistically correct.

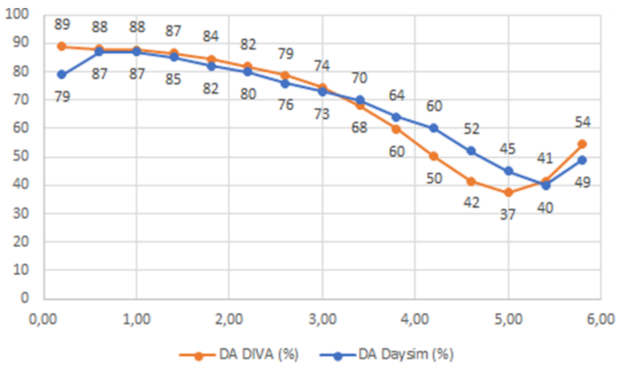

Figure 4. Case study DA values comparison

The deviation percentage may be caused by multiple factors mainly due to important differences between DIVA and DaySim, as the environment turbidity value (which is not editable) or the projected shadow of the window sill, which DIVA does not consider.

F. Calculation Variables Definition.

There have been considered several variables for calculating the model that can also be grouped in two main epigraphs.

The first one is referred to the model physical variables as window gap size (Table IV) and the materials reflectance (Table V).

TABLE IV. WINDOW GAP SIZE VARIABLES SET

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

TABLE V. MATERIALS INTERIOR 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 one is about the model conditions variables, where it can be found the location of the model (Madrid and London) and the orientation of the window (north and south).

All these variables are combined as shows the 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
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
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
30CB_LN	30	0.80	0.50	0.80	0.75	London	North
30CD_LN	30	0.60	0.20	0.40	0.75	London	North
60CB_LN	60	0.80	0.50	0.80	0.75	London	North
60CD_LN	60	0.60	0.20	0.40	0.75	London	North
30CB_LS	30	0.80	0.50	0.80	0.75	London	South
30CD_LS	30	0.60	0.20	0.40	0.75	London	South
60CB_LS	60	0.80	0.50	0.80	0.75	London	South
60CD_LS	60	0.60	0.20	0.40	0.75	London	South

Finally, these hypotheses are combined with the seasonal occupation schedules, studying both the whole standard year with no holidays for regular Daylight Autonomy (DA) calculation and the same year without occupation during July and August for Partial Daylight Autonomy (Dap) calculation, considering in this way the Spanish summer vacation period. That is why this metric is expressed as DAp [500lx, 255-165], referring to the illuminance threshold given (500 lux) and an annual period of time specified in days.

E. Results Analysis Tools Definition.

The result obtained from the calculating process have been analysed from two different perspectives.

Firstly, a graphic analysis has been made, studying the behaviour pattern of each one in order to group them, making it possible to understand the light input in every model variation.

Secondly, it has been done a deviation analysis, specifically considering the mean and standard deviation for each model variation, so that it has been possible to mathematically understand and see how every model behaves and how it numerically impacts the use of DA against the use of DAp [500lx, 255-165].

IV. CALCULATING AND ANALYSIS OF RESULTS

Every model variation, those specified in the Table VI (up to 16 different variations), has been calculated with DIVA and compared each model with the same one that just modifies the occupation schedule, so that it has been possible to compare a classroom in any of the specified conditions considering summer vacations without occupation (obtaining the DAp) and the whole year with occupation (obtaining the DA).

In the graphic analysis, it has been possible to group every graphic into a behaviour group, so that the group number is up to four. Group A (Fig. 5) is for graphics that follow the pattern of two functions decreasing (being DA always higher than DAp) as they ward off the facade, but never cross between them nor reach the zero value; every model characterised by a *bright* level of reflectance is included in this group.

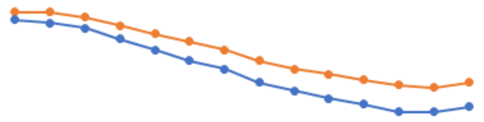

Figure 5. Group A graphics example

Group B (Fig. 6) is for graphics that follow the same pattern as those in group A, except for reaching the zero value as they approach to the background; almost every model characterised by a *dark* level of reflectance is included in this group.

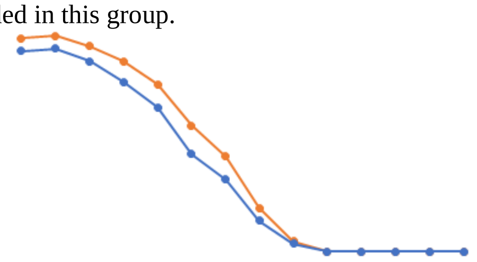

Figure 6. Group B graphics example

Group C (Fig. 7) is for graphics that, although the beginning of the functions is the same as those from group A and B, there is a point where the functions cross between them and it is the DAp function the one that is higher; the majority of this graphics are those characterised by a *dark* level of reflectance, as well as by a south orientation. Moreover, considering that cross of values, it is possible to affirm that there is no lineal correlation between DA and DAp.

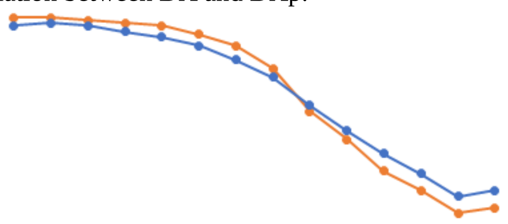

Figure 7. Group C graphics example

Group D (Fig. 8) is for graphics that, although in the initially they follow the same pattern as those in group A, it is noticeable that the divergence between every value decreases as they approach to the background, tending to cross, yet it does not happen because of the depth that, if the classroom was deeper, it clearly would show the cross of the values as in group C.

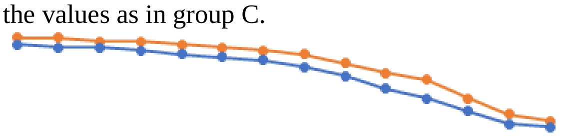

Figure 8. Group A graphics example

On the other hand, it has also been made a deviation analysis, considering that deviation about location, orientation, reflectance and window gap size.

About the location, those models located in London have showed a higher deviation between DA and DAp.

Considering the orientation, the values prove that the divergence between DA and DAp is higher in the models oriented to north.

Taking into account the reflectance, the deviation between the *bright* models and the *dark* models show are barely the same, which shows that the reflectance is not a determining factor in the efficiency of using DA or DAp.

Lastly, deviation in models with a 30% or 60% of window size in facade are quite similar, although it can be appreciated a slightly higher difference as the size decreases.

V. Conclusions

According to the analysis and results of this methodological example, the use of this new dynamic metric, Partial Daylight Autonomy (DAp), means a higher adjustment in the results of daylighting calculations for seasonal use spaces.

Moreover, it is noticed that the higher level of diffuse radiation exposure of the model, the greater the divergence between DA and DAp metrics, so models with north orientation or being located somewhere with similar sky conditions as London are the most sensitive to the use of the DAp indicator. Furthermore, the impact of the size of the window plays a more importat role in the DAp metric than reflectance (although a bright inner envelope always means an improvement in the calculations). In addition, there is no lineal correlation between Daylight Autonomy (DA) and Partial Daylight Autonomy (DAp), showing the importance of considering this new metric, as it cannot be directly deduced from DA. Finally, electric lighting support tends to be necessary for classroom models with *dark* reflectance and oriented to north because of low values of DA and DAp, which mean a total or almost total dependence of electricity.

In conclusion, this work shows that use of DAp indicator significantly increases the accuracy by predicting the annual use of daylight in buildings with seasonal use, also showing that there is not a direct relationship with the DA indicator.

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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