Weighting Factors for Dynamic Metrics in Natural Lighting: Application to Office Rooms

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***Abstract*— Considering the work requirements and the current way of life, human beings spend more and more hours a day indoors. Therefore, it is essential to make an appropriate optimization of windows in architecture, to reduce energy consumption and its impact on the environment, as well as an improvement in the health and wellness of the occupants by promoting a suitable circadian cycle.**

This study aims to simplify the calculation of daylighting in interior spaces, establishing a more precise link between one of the most common static metrics, the Daylight Factor (DF) and another of the main dynamic metrics, the Daylight Autonomy (DA), linking them through the Minimum Daylight Autonomy (DAm), allowing to obtain precise dynamic daylighting values without the need for a sophisticated and slow computational simulation.

In this way, a work methodology is proposed and applied as a practical example in 6 European capital cities with different latitudes and sky types, quantifying the relationship between both metrics for each of them and analysing the current tendencies of the results. The work concludes with a first transposition of the results of the study samples, allowing its easy and fast application of this link to any professional of Architecture.

***Index Terms*—Natural lighting, dynamic metrics, energy efficiency, architecture and health, minimum daylight autonomy, weighting factors**

I. INTRODUCTION

Nowadays, society is more and more conscious of the importance of sustainable development. Under the current European normative context, the 20-20-20 objective and the 2010 EPBD directive, all new buildings will be almost zero consumption from 2020.

In the case of electric lighting, in Spain it supposes 28.1% of the global energy consumption in services buildings [1]. Therefore, an architectural design that makes appropriate use of sunlight can save energy consumed [2]–[4] and also improve comfort, both lighting and thermal [5]. In addition, several studies link natural lighting with the stimulation of the circadian cycle, which regulates melatonin levels and therefore improves people's quality of life [4], [6]–[11].

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Traditionally, the dimensioning of windows in architecture were designed for aesthetic reasons, without taking account of quantitative criteria of optimization and energy use, but the sophistication of the calculation methods and new metrics of natural lighting have opened a new way to improve window [12] and lighting smart control designs [13], [14].

Actually, dynamic metrics such as Daylight Autonomy (DA) [15] get a better precision in the lighting calculation, because they take into account parameters such as orientation, location and sky types, which do not consider other metrics such as DF.

In 2019 Minimum Daylight Autonomy (DAm) metric is developed by Acosta et al [16], which is calculated algebraically through the DF and other parameters to obtain the Daylight Autonomy with overcast sky conditions during all the year (which means the minimum value of Daylight Autonomy), also opening the possibility to determine a link to the DA in further studies.

Thus, this study pretends to study and improve the link between the DAm and the DA analysing the weighting factors in 6 European capital cities.

II. OBJETIVES

The main objective of this work is to simplify the calculation process of the Daylight Autonomy (DA) [15] from the Daylight Factor (DF), using for it the Minimum Daylight Autonomy (DAm) as a bridge. In this way, it is necessary to obtain more precise Weights factors (WF) [17]. For this purpose, methodological guidelines are established to define a more precise link between both metrics, using a standard office module in different locations as a common and widespread case study.

III. METHODOLOGY

A. Selecting the Room Model.

The case study is a standard office room, with the dimensions of 3 metres wide, 6 metres deep and 3 metres high. It has a window of variable dimensions in the centre of the exterior facade. This model is the same used in previous studies by Acosta et al. [4], so its use allows its replication, in order to do a validation of results comparing them with the results obtained in this publication.

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The orientation chosen for this study is north, with the model's envelope having the following photometric characteristics:

TABLE I. SURFACE CHARACTERISTICS OF MATERIALS USED

Materials	Surface Characteristics			
	Floor	Walls	Ceiling	Glass
Reflectance	0.60	0.80	0.80	0.90
Solar Transmittance	0.00	0.00	0.00	0.70

Its interior is discretised by a grid of points superposed of 0.3 m x 0.3 m, located at a height of 0.6 m from the interior surface of the floor model, emulating the usual working plane of an office, as shows Fig. 1. From this grid, the central longitudinal section is taken for analysis.

The occupation period is defined from 8:00 to 17:00 from Monday to Friday, without lunch break and including Daylight Saving Time (DST).

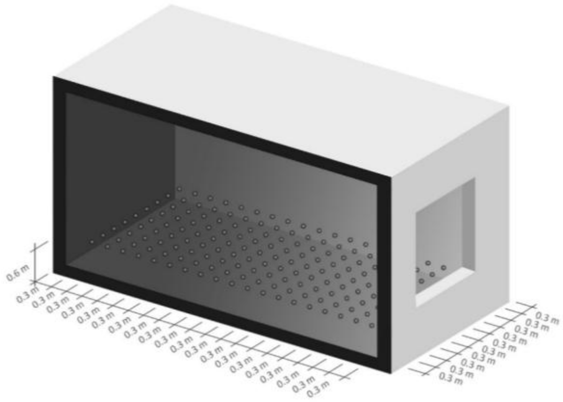

Figure 1. Space between calculation points.

B. Selection of Variables

The study example is based on two variables:

- Location (Include different latitudes and sky models).
- Window size.

The climatic data used for this study correspond to the following locations (Table II):

These locations have been chosen between latitude 55 º and 40 º north, because they are latitudes where there is a higher population density and there is more weather data, the results of the calculation could be extrapolated to the southern hemisphere because the solar behaviour is similar in both hemispheres at same latitudes. It would be interesting, in future studies, to carry out this verification in different latitudes.

TABLE II. UNDER-STUDY LOCATIONS WITH ASSOCIATED LATITUDES

Location	Latitude (North)	Location	Latitude (North)
Copenhagen (Denmark)	55 º	Berlin (Germany)	52 º
Warsaw (Poland)	52 º	Paris (France)	48 º
Vienna (Austria)	48 º	Naples (Italy)	40 º

The window size will be squared and centred in the wall, changing between two values of window-facade ratio: 20 and 40%.

C. Selecting the Calculation and Validation Tool

This study has been carried out with DIVA 4.0 from Solemma, which uses the Rhinoceros 5.0 modelling interface. This tool uses the latest version of C. Reinhart's Radiance engine, validated by the international scientific community.

The light calculation algorithm used by this tool is based on the *Daylight Coefficients* developed by Maldarjevic [18].

This calculation model was previously used in previous studies by Acosta et al. [4], where the DF and DA were calculated with DAYSIM 3.2, a software based also on the previous version of the Radiance engine of C. Reinhart. Therefore, if the results obtained in DIVA 4.0 are similar to those of DAYSIM for the same model and under the same parameters, these could be considered validated, given that these studies were calibrated with a comparison with a real model based on an existing test cell built in Seville and monitored for a full year [19], [20].

To make this calibration, the physical characteristics of the calculation model chosen for this work correspond to those calculated in the Acosta et al. [4] publication, the comparison of the value of the Daylight Factor for each of the nodes in model 3.6.3.20 is made, which correspond to the office model with a small window of 20%.

TABLE III. RADIANCE CALCULATION PARAMETERS IN DAYSIM 3.2 AND DIVA

Parameter	Value	Parameter	Value
Ambient Bounces	7	Specular Jitter	1.0000
Ambient Divisions	1500	Limit Weight	0.0040
Ambient Super-Samples	100	Direct Jitter	0.0000
Ambient Resolution	300	Direct Sampling	0.2000
Ambient Accuracy	0.05	Direct Relays	2
Limit Reflection	10	Direct Pre-test Density	512
Specular Threshold	0.0000		

The work schedule is from 8:00 a.m. to 5:00 p.m. Monday to Friday, excluding weekends, no lunch break and including Daylight Saving Time (DST).

After the comparative study, and as can be seen in Fig. 2, it can be concluded that the results obtained with DIVA are practically similar to DAYSIM with an average deviation of less than 0.38, caused mainly by the difference in the area closest to the window (0.45 m point).

This deviation may be attributed to the shadow projected by the parapet of the window, causing small variations in the DF for each calculation program, because DAYSIM does not require a three-dimensional modelling of the window aperture, which is different from DIVA.

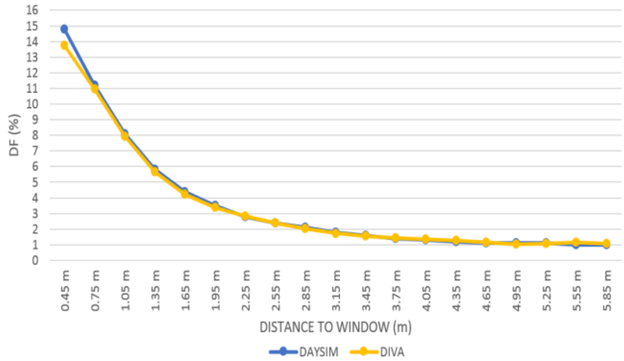

Figure 2. Comparison of DF values between DAYSIM and DIVA.

D. *Generation and Analysis of Weighting Factors (WF) from Acosta et al. Algorithm* [16].

Knowing the DA and DAm values, through the Acosta et al. algorithm [16] corresponding to equation 1, it is possible to obtain the weighting factor (WF) for each of the DA values previously calculated with DIVA from the DAm, then making an arithmetic average for each of the models, in order to find the mean WF for each model.

$$DA_{DAm} = DA_M + (1 - DAm) \cdot WF \cdot d^{0.25} \quad (1)$$

Where DA_{DAm} is the Daylight Autonomy calculated from DA_M, *DAm* is the Minimum Daylight Autonomy, *WF* is the Weighting Factor, and *d* is the distance (m) between the point studied and the facade.

This WF value allows to incorporate the influence in the calculations of the location (latitude and sky conditions) and the orientation, among other factors.

IV. Calculating and Analysis of Results

The values obtained in each model for Daylight Factor (DF) and Daylight Autonomy (DA), as well the values of Minimum Daylight Autonomy (DAm) calculated from DF are shown in Table IV.

It should be noted that these values of WF only shows the impact of the location (latitude and sky conditions), given that all the models are facing north, so the influence of the orientation is not reflected.

TABLE IV. Mean Values of DF, DA and DA_{DAM} for the Locations under Study

Location	20% Window-Facade			40% Window-Facade		
	DF	DAm	DA	DF	DAm	DA
Copenhagen (Denmark)	4.0	24.5	46.7	6.5	43.6	69.9
Berlin (Germany)	4.0	26.4	46.9	6.5	46.9	70.3
Warsaw (Poland)	4.0	27.3	46.6	6.5	48.4	68.2
Paris (France)	4.0	26.6	54.6	6.5	47.6	77.7
Vienna (Austria)	4.0	30.7	50.3	6.5	54.4	74.1
Naples (Italy)	4.0	32.9	59.7	6.5	58.2	83.6

The values of the Weighting Factors (WF) are shown in Table V).

TABLE V. Values of the Weighting Factors (WF) for the Locations under Study

Location	20% Window-Facade	40% Window-Facade
Copenhagen (Denmark)	0.41	0.36
Berlin (Germany)	0.37	0.33
Warsaw (Poland)	0.28	0.23
Paris (France)	0.33	0.47
Vienna (Austria)	0.36	0.31
Naples (Italy)	0.47	0.41

From these WF factors, equation 2 is proposed to show the impact of the window size and linking the % of this window in the facade and the location, showing a small divergence between them of 0.025 in the locations under study.

$$B = 0.87 \cdot A \quad (2)$$

Where B is the window size of 40% and A the size of 20%.

Once the proportion between a 40% window and a 20% window has been calculated, replacing these values in the equations of the system, a comparison of the Weighting factor (WF) between the different locations studied can be made, allowing us to know which cities have the highest WF.

Performed in all calculation models, the compare between them of the weighting factors due to the location, a comparative analysis can be made with all of them.

As can be seen, the DA_{DAm} results are adequately adapted to the cities under study for both window sizes, showing all of them a low standard deviation, no higher than 0.08 in any of the cases. As an example, Fig. 3 and Fig. 4 show the comparison between window sizes in the location of Berlin.

In this way, it is demonstrated that the link established for these cities is valid and results can be obtained with good precision using this new link.

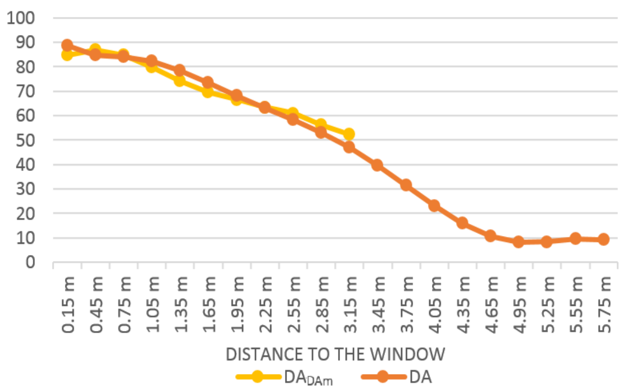

Figure 3. Comparison between DA and DA_{DAm} in Berlin with a 20% window to facade ratio.

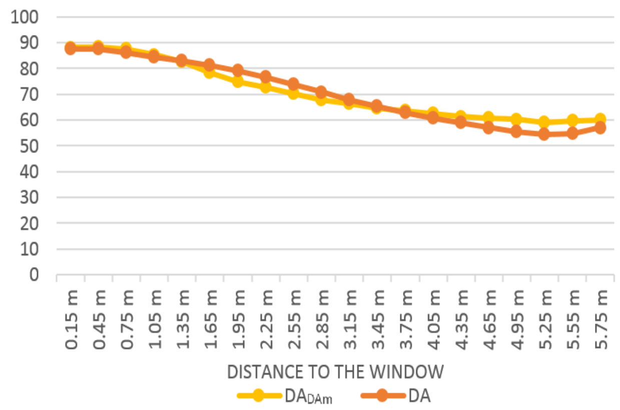

Figure 4. Comparison between DA and DA_{DAm} in Berlin with a 40% window to facade ratio.

V. Conclusions

In conclusion, static and dynamic metrics have been more exactly linked using developed weighting factors, allowing more efficient daylighting calculations for the locations studied.

The calculation methodology has been established in order to develop new weighing factors in future investigations that will allow the calculation to be made in other locations.

It has been determined that there is a very good adaptation between the DA and the DA calculated through the DAm (DA_{DAm}) in the locations under study.

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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