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Minimum daylight autonomy: A new concept to link daylight dynamic metrics with daylight factors

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Abstract

Daylight metrics act as a useful tool to quantify the potential of natural light in an architectural space as well as the energy saving promoted by a suitable design of windows, atriums and skylights. Accordingly, a new indoor lighting metric is proposed, Minimum Daylight Autonomy, defined as the percentage of occupied time when an illuminance threshold can be met by daylight alone under continuous overcast sky conditions. This novel concept can determine an approximation of the maximum use of electric lighting and the quantification of minimum energy savings without the need for advanced calculation tools. Although Daylight Factor is the most widespread concept, it cannot forecast energy saving as accurately as dynamic metrics. In addition, Daylight Autonomy is the most usual dynamic definition, since it estimates the energy consumption of on/off electric lighting systems depending on weather conditions. However, there is no link between static and dynamic metrics, as both concepts are based on different variables. This research proposes the calculation procedure for Minimum Daylight Autonomy, as well as the equations which serve to predict dynamic metrics based on static, after confirming the accuracy of the simulation program which calculates the metrics using a test cell under real conditions.

Keywords: daylighting, energy management, daylight factor, daylight autonomy, daylight metric.

1. Introduction

1.1. State of the art

In the current scenario of building design, the analysis of energy savings is crucial to define a sustainable construction. As electric lighting involves between 15 and 30% of the total energy consumption in buildings [Ryckaert 2010, Lam 2003, Armaroli 2011], it is advisable to pay attention to the use of natural lighting. Accordingly, a proper architectural design can allow a reduction in energy consumption in electric lighting [Acosta 2015a], based mainly on the quantification of daylighting metrics [Leslie 2012].

A suitable window design can noticeably impact electric energy consumption, as concluded in the study by Leslie et al. [2005], which quantify the effect of blind controls in energy saving according to the calculation of simulated Daylight Factors (DF). This metric can also be useful in determining the suitable design of atriums [Acosta 2018, Calcagni 2004], courtyards [Acosta 2014] and skylights [Kim 2011, Acosta 2012, Campano 2014], as deduced from previous studies. Other researchers, such as Acosta et al. [2016, 2017], determine the impact of window size and position on electric energy consumption by means of the analysis of daylight dynamic metrics. Daylight Autonomy (DA) specifically has been used in recent years in several studies [Muñoz 2014, Mangkuto 2016, Vanhoutteghem 2015] to properly quantify the sustainability of the building design. Other dynamic metrics such as Useful Daylight Illuminance (UDI) have demonstrated a practical application for windows and atrium design [Berardi 2015].

The most usual metric for determining natural light in building design is DF, which defines the ratio of the inner illuminance at given point to that measured outside under overcast sky conditions [CIE 2011]. Nowadays, DF is the most widespread concept in the analysis of daylighting [Chel 2010, Chow 2013]. As it can be considered a static metric, its results only depend on the qualities and geometry of the architecture, since orientation and location are irrelevant considering an ideal cloudy sky [CIE 2003]. Therefore, DF defines the potential illuminance at a studied point under overcast sky conditions. In accordance with this definition, the illuminance measured at an interior point can be deduced knowing the external illuminance.

However, DF is not a fully reliable metric when quantifying the energy consumption in electric lighting, since it ignores natural light provided under clear sky conditions and the illuminance thresholds required in order to execute the task [Boyce 2013]. Therefore, as stated before, the use of dynamic metrics in lighting research is becoming increasingly frequent, and energy savings are determined in accordance with the opening orientation, room location and luminance conditions of the sky vault. The most extended dynamic metric is probably that of DA, proposed in 1989 by the Association Suisse des Electriciens [1989] and redefined by Reinhart et al. [2006]. DA is defined as the percentage of the occupancy time during the year when a minimum illuminance threshold is met by daylight alone. Accordingly, the higher the DA value, the lower the switching on time of electric lighting.

Several new metrics based on DA emerged subsequently, aiming to determine the autonomy of natural light according to vision adaptability or the dimming control of electric lighting. Accordingly, Continuous Daylight Autonomy (DAcon) was proposed [Reinhart 2006]. This metric is defined as the percentage of the occupied time during the year when a minimum illuminance threshold is met by daylight alone, considering a partial credit linearly to values below the threshold defined. Although the use of this novel concept is not as widespread as DA, it can be useful in certain circumstances. For example, Ahadi et al. [2017] used this metric to assess the daylight performance of light-wells and courtyards.

One of the most relevant dynamic metrics is UDI, which determines when daylight levels are suitable for occupants [Nabil 2005, 2006]. Nabil et al. developed this new metric, based on the percentage of the occupied time during the year when the illuminance value is between 100 and 3,000 lux [Mardaljevic 2012]. An illuminance level below 100 lux is considered fell-short, while a value higher than 3,000 lux is defined as exceeded. As explained above, UDI has made it possible to determine an efficient architectural design for daylight harvesting [Al-Obaidi 2015, Kleindienst 2013]. A suitable value for UDI, as well as for DA, can be 50% [Reinhart 2014].

Most recently, the Illuminating Engineering Society of North America (IESNA) published a new method to analyze the daylight potential of architectural spaces. This method is based on the new metric of Spatial Daylight Autonomy (sDA), which describes the percentage of floor area that receives an illuminance level higher than or equal to 300 lux during at least 50% of the annual occupied hours [IESNA 2013]. Accordingly, this concept does not refer to a given point, since it analyzes daylight use for an entire surface. Several researchers have reasoned their results for the application of this metric [Verso 2017, Kazanasmaz 2016].

As deduced from this brief introduction, there is a wide range of daylight metrics with no link between them. This in turn makes it difficult for designers to choose a suitable metric when assessing the potential of natural light of an architectural space.

1.2. Aim and objectives

In accordance with the previous scenario, where static and dynamic metrics coexist with no link between them, the Minimum Daylight Autonomy (DAm), defined as the percentage of the occupied time when an illuminance threshold can be met by daylight alone under a continuous overcast sky conditions, is proposed. This novel concept serves to determine the use of electric lighting and the quantification of energy savings under the worst case scenario without requiring advanced calculation tools, since weather conditions always correspond to a cloudy sky. Thus, the minimum energy savings produced by an electric lighting facility can be quantified, assuming a daylight responsive control system. DAm is therefore based on the DA procedure, although considering the variables for DF calculation. Thus, this metric can be used to link static and dynamic metrics, as explained in this study.

This research aims to determine the calculation procedure for DAm, as well as the links of this new concept to static and dynamic metrics. DAm can be quantified following a simple procedure explained below, so that the entire calculation process can be included in a spreadsheet. To bridge the gap between static and dynamic metrics, equivalence tables have been designed to determine the DAm value according to DF and the latitude of the location studied. Moreover, the relationship of DAm with other dynamic metrics such as DA is determined using weighting factors which depend on weather conditions and window orientation. This can therefore be a useful tool for lighting designers.

2. Methods

2.1. Definition of DAm

DAm is defined as the percentage of the year when a minimum illuminance threshold is met by daylight alone, considering overcast sky conditions throughout the year. Therefore, the higher the DAm, the higher the minimum energy saving in electric lighting. Based on this definition, this metric can be quantified as equation (1):

$$DAm = \frac{\sum_i wf_i \cdot T_i}{\sum_i T_i} \in [0,1];\ wf_i = \begin{cases} 1\ if\ E_{DO} \geq E_L \\ 0\ if\ E_{DO} < E_L \end{cases} \quad (1)$$

where T_i is the occupied time in a year, wf_i is the weighting factor which depends on the illuminance threshold, E_{DO} is the daylight illuminance measured at a given point under overcast sky conditions, and E_L is the illuminance threshold.

This new concept can be used to link dynamic metrics such as DA or UDI, with DF, finding commonalities between static and dynamic definitions. DAm is reasoned following the concepts of other dynamic metrics [Reinhart 2006] although it is based on the variables established for the DF calculation [CIE 2011].

Unlike other dynamic metrics, DAm can be calculated analytically, considering the Moon-Spencer definition of an ideal overcast sky [Moon 1942] and the zenith luminance calculation [Karayel 1984]. A simplified calculation procedure is shown below.

2.2. Simplified calculation procedure for DAm

2.2.1. Protocol

The calculation of DAm relies on interior illuminance, which depends on solar altitude and sky conditions. Subsequently, the illuminance calculated helps to determine the percentage of time during which this value is equal to or higher than the illuminance threshold chosen, as defined in equation (1). Accordingly, the calculation procedure is defined as in Figure 1:

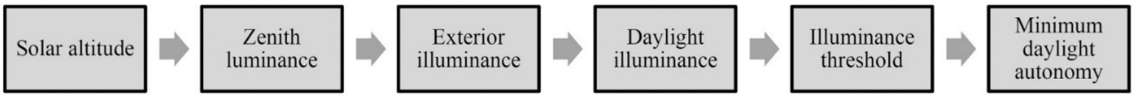

Figure 1: Procedure for calculating minimum daylight autonomy.

2.2.2. Equation of time

In order to properly determine solar time, which serves to define the altitude of the Sun, the time equation must be used. This equation gives the difference between solar time and clock time due to the elliptical orbit of the earth and solar declination of the axis [IESNA 2000]. This divergence goes from -14:15 minutes on February 11 to +16:25 minutes on November 3, varying throughout the year.

Several procedures can be used to calculate the equation of time. Lamm proposed a simple method to calculate the divergence between solar and clock time [Lamm 1981] widely used for most terrestrial daylighting calculations, while Meeus defined a complex procedure focused on astronomical calculators [Meeus 1988]. The formulae (2) used in this research correspond to a variant of the Meeus procedure which can be easily implemented in most calculation engines.

$$ET = -\left[9.87\,sin\,2\left(\frac{(J-36605)360}{365.25}\right) - 7.53cos\left(\frac{(J-36605)360}{365.25}\right) - 1.5sin\left(\frac{(J-36605)360}{365.25}\right)\right] \quad (2)$$

where *ET* is the difference between solar time and clock time, measured in minutes and *J* is the Julian date, a number between 1 and 365.

It is worth noting that the accuracy of the time equation is not decisive in the calculation of DAm, since the variation between different procedures diverges by barely a few seconds.

2.2.3. Solar time

The solar time [IESNA 2000] is calculated according to the following formula (3):

$$t = t_s + \frac{ET}{60} + \frac{12(SM-L)}{\pi} \quad (3)$$

where t is the solar time in decimal hours; t_s is the standard time in decimal hours, which is equal to daylight time minus one hour; *ET* is the equation of time measured in minutes; *SM* is the standard meridian for the time zone in radians; and *L* is the site longitude in radians.

It should be noted that daylight saving time plays an important role in determining local time. Therefore, one hour must be added during the winter season and two hours throughout the summer season.

2.2.4. Declination

The declination of the Sun [IESNA 2000] is determined according to the following equation (4):

$$\delta = 0{,}4093\, sin\left(\frac{2\pi(J-81)}{368}\right) \quad (4)$$

where δ is the declination in radians and J is the Julian date.

2.2.5. Solar altitude

The solar altitude [IESNA 2000] can be defined through the equation below (5):

$$a_t = \arcsin\left(sinl \cdot sin\delta - cosl \cdot cos\delta \cdot cos\frac{\pi t}{12}\right) \quad (5)$$

where a_t is the solar altitude in radians, l is the site latitude in radians, δ is the declination in radians, and t is the solar time in decimal hours.

Solar elevation is key to determining DAm, as the luminance of the sky vault depends on this variable.

2.2.6. Zenith luminance

There are many methods proposed to determine zenith luminance, depending on sky conditions, turbidity of the atmosphere and solar altitude. One of the first approaches proposed was by Karayel et al. [Karayel 1984] depending on solar altitude and Linke's turbidity factor. Other researchers have studied the zenith luminance for a specific location [Lam 2003, Soler 2004] due to the divergence of the results obtained with the previous formulation. Therefore, there is no universal method to estimate zenith illuminance [Ferraro 2012]. The formula proposed (6) for this simplified procedure is the one defined in most architecture handbooks [Baker 1993] and determined by Nakamura et al. [1985].

$$L_{ZO} = 100 + 7580(\sin{(a_t)})^{1.36} \quad (6)$$

where L_{ZO} is the zenith luminance under overcast sky conditions in cd/m² and a_t is the solar altitude in radians. It should be highlighted that there are many procedures to calculate zenith luminance and the DAm calculation will vary according to the formulation used. As an example, using the calculation formula developed in the Lighting Handbook [IESNA 2000], the DAm measurements increase in comparison with the method described in this procedure.

2.2.7. Exterior illuminance

Exterior illuminance can be defined based on the luminance of the sky vault. As explained above, DAm is obtained considering overcast sky conditions throughout the year, so that sky luminance can be determined following the Moon-Spencer definition [Moon 1942], as expressed in (7):

$$L_{\theta O} = \frac{L_{zO}(1 + 2sin\theta)}{3} \quad (7)$$

where $L_{\theta O}$ is the luminance at solar altitude and L_{ZO} is the luminance at the zenith, both under overcast sky conditions and measured in cd/m². Accordingly, the exterior illuminance from an unobstructed sky vault under overcast sky conditions is defined in (8):

$$E_{EO} = 2\pi \int_0^{\frac{\pi}{2}} \frac{L_{zO}(1 + 2sin\theta)}{3} cos\theta sin\theta \, d\theta = \frac{2\pi L_{zO}}{3} \cdot \left(\left[\frac{-cos2\theta}{4}\right]_0^{\frac{\pi}{2}} + 2 \cdot \left[\frac{sin^3\theta}{3}\right]_0^{\frac{\pi}{2}} \right) = \frac{7\pi L_{zO}}{9} \quad (8)$$

where E_{EO} is the exterior illuminance in lx and L_{ZO} is the luminance at the zenith in cd/m² under overcast sky conditions, as expressed in (6).

It is worth noting that there are several methods for determining the luminance distribution of an overcast sky vault, most notably the equations by Perez et al. [1993], which can also be used for this purpose, as can be deduced from the CIE [2003]. The Perez et al. formulas allow not only the calculation of luminance distribution of an overcast sky, but also for intermediate and clear skies. The luminance distribution of the sky can affect to the outer and inner illuminance measures, modifying the DF calculation as well as the expected DAm results. It should be also noted that an overcast sky usually corresponds to the worst case scenario for measuring internal illuminance, but this statement must be taken with caution, since in specific situations, such as for high latitudes, early and late hours of the day and a window orientation avoiding sunlight, a clear sky might provide a lower sky component.

2.2.8. Daylight illuminance

Daylight illuminance measured in the interior space can be deduced based on the exterior illuminance and DF [CIE 2011]. DF can be calculated using calculation programs [Acosta 2012] or predictive methods [Acosta 2014]. Daylight illuminance can thus be expressed as (9):

$$E_{DO} = DF \cdot E_{EO} \quad (9)$$

where E_{DO} is the daylight illuminance measured at a study point, DF is the daylight factor at the same point and E_{EO} is the exterior illuminance under overcast sky conditions.

2.2.9. Illuminance threshold

As in the case of other dynamic metrics, the illuminance threshold must be defined to calculate DAm. This value depends on the illuminance requirements of the task and usually ranges from 100 to 500 lux.

2.2.10. Minimum daylight autonomy calculation

Finally, DAm is calculated, according to the illuminance threshold and the occupancy hours. Following equation (1), DAm can be defined as expression (10):

$$DAm = \frac{\sum_i wf_i \cdot T_i}{\sum_i T_i} \in [0,1];\ wf_i = \begin{cases} 1\ if\ E_{DO} \geq E_L \\ 0\ if\ E_{DO} < E_L \end{cases} \quad (10)$$

where T_i is the occupied time in a year, wf_i is the weighting factor which depends on the illuminance threshold, E_{DO} is the daylight illuminance measured at a given point under overcast sky conditions, and E_L is the illuminance threshold. For practical purposes, the occupied time can be measured in hours, considering the occupancy hours throughout the year.

An interesting approach for calculating DAm can be based on time frames shorter than a whole year. As an example, this metric can be determined considering the illuminance measured during winter season, showing a worse scenario than that observed for the entire year. Under this new focus, the comparison of this concept with DA might not carried out, but it could be useful for analyzing certain periods of the year.

In accordance with the definition stated, solar elevation determines illuminance at the studied point and the threshold selected allows the calculation of the percentage of hours during the year when a suitable level is met by the natural light provided by a constant cloudy sky. For example, using a color scale from red to green through yellow, Figure 2 shows the hours throughout the year when a minimum threshold of 100 lux is met according to a DF value of 2%. This calculation process has been carried out only using a spreadsheet. Considering an occupied time from 8 am to 5 pm, DAm corresponds to 84% for equator, 79% for latitude 20°, 70% for latitude 40° and 46% for near Artic Circle, at latitude 60°. As deduced, DAm values decrease in accordance with latitude, due to the illuminance threshold and the occupancy hours defined.

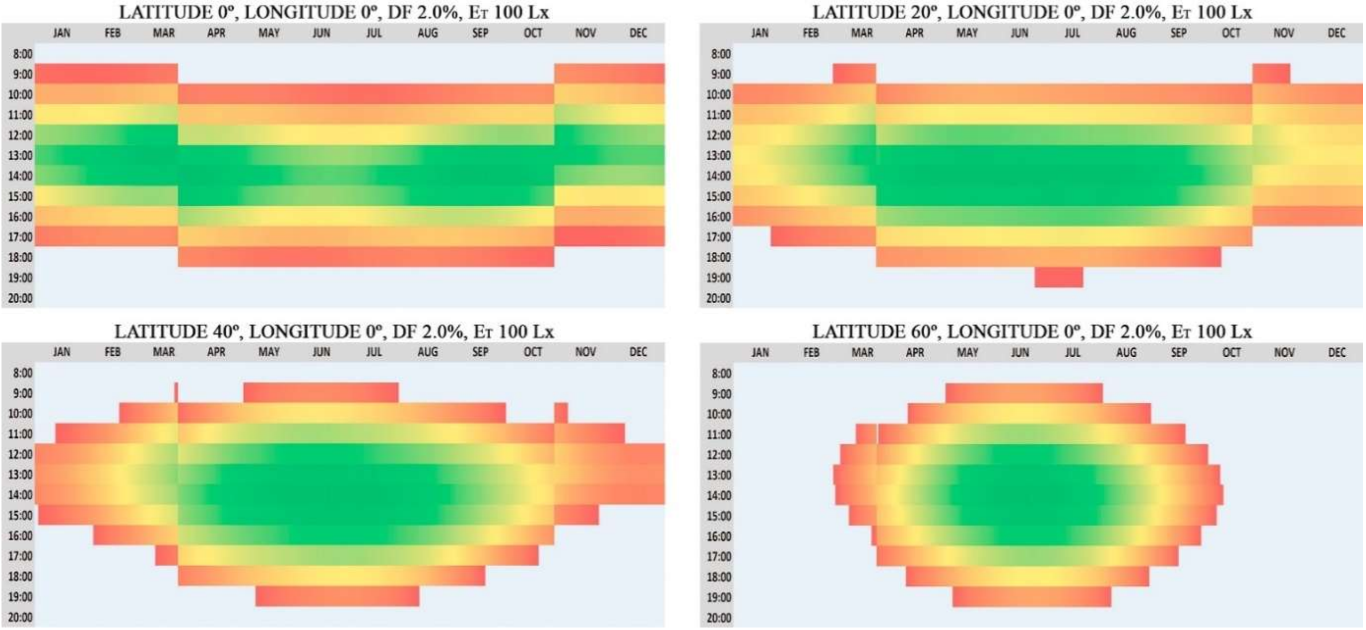

Figure 2: Calculation of Minimum Daylight Autonomy (DAm) for different latitudes, a Daylight Factor (DF) of 2% and an illuminance threshold of 100 lux.

The asymmetry observed in the color maps of Figure 2 is the result of the application of the equation of time and the daylight saving time, which clearly affect the illuminance measured according to local time.

2.3. Validation of the calculation tool

In order to find a link between DAm and the dynamic metrics mentioned above, a calculation procedure is carried out using a simulation program. Daysim 3.1 software uses the Radiance engine to predict the amount of daylight in buildings, based on direct and diffuse horizontal irradiances provided by a climate file. Although this simulation program has previously been tested by several researchers [Reinhart 2001, Acosta 2015b], a validation process is required to define its accuracy in calculating both DA and DF, comparing the simulated results with those measured in a test cell under real conditions.

2.3.1. Characteristics of the test cell and the calculation model

This study was developed using a test cell placed in Seville (Spain) [León 2017]. This south-facing cell is 2.40 m wide, 3.20 m deep and 2.70 m high. The whole enclosure, made of sandwich panels including the roof and floor, is highly insulated. Its south-facing facade has a window 108 cm high by 116 cm wide, with double glazing (2x4mm glass with 8 mm air-space) and an aluminum sliding frame. The glazing fraction has a solar factor of 0.85 and a visible transmittance of 0.75. The maintenance factor, which represents the dirt buildup on the window, is considered 0.80. The inner envelope has a reflectance of 0.72 for walls and ceiling and 0.22 for the floor.

Illuminance data were collected throughout 2017 using 8 inner illuminance-meters (range of 20-2,000 lx, accuracy of ±3.0%), located above the floor spaced at 0.40 m on the axis of symmetry of the cell, as Figure 3 shows. An outdoor illuminance-meter (range of 0-150,000 lx, accuracy of ±0.4%) was used to measure the illuminance outside the cell.

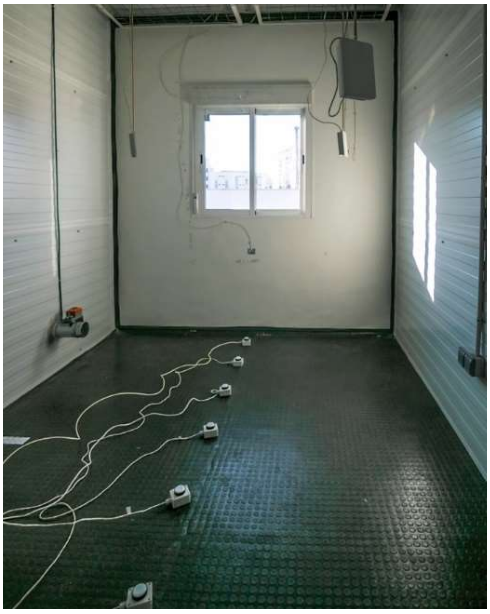

Figure 3: Test cell inner view with the distribution of the illuminance-meters.

These sensors are represented in the calculation model by a superimposed grid of monitor points. The calculation parameters used for Daysim 3.1 are listed in Table 1. The weather conditions used in the validation study correspond to Seville (Spain), at Latitude 37.42º and Longitude 5.40º, with mainly clear skies. These weather data were collected from the SEVILLA SWEC file (Spanish Weather for Energy Calculations) developed by Pérez-Lombard for the Spanish National Institute of Meteorology (AEMET) [De la Flor 2008].

Table 1: Parameters of the calculation program.

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

2.3.2. Boundary conditions for DA and DF calculation

The daylight autonomy was calculated with an occupancy schedule from 8:00 to 17:00, with no lunch break or blind control, since the window has no blinds or other shading devices. These conditions have been considered both for computer simulation and for measurements. In addition, 100, 250 and 500 lux were established as indoor illuminance thresholds for DA calculation as they represent average illuminance values for architectural spaces.

The DF of each sensor location was calculated as an average of the illuminance values measured for the days in 2017 which correspond to overcast sky conditions close to the Moon-Spencer model [Moon 1942].

The overcast sky selected for DF calculations met the following conditions:

- The sky ratio, determined by the quotient of the horizontal sky irradiance to the global sky irradiance, must be higher than 0.85.
- The luminance measured at the four cardinal points, with an elevation of 30°, must be similar, with an absolute margin of error lower than ±5%.
- The exterior illuminance must be close to 7πLz/9, where Lz is the luminance in the zenith, with an absolute margin of error lower than ±10%.

2.3.3. Results of the validation process

Figure 4 shows the DA and DF values calculated for the validation process. The first graph compares DA results from measurements and computer simulations for the defined illuminance thresholds (100, 250 and 500 lux), as well as their different absolute percentages. The second graph shows the DF results both from simulation and the average measurements, also showing their absolute difference.

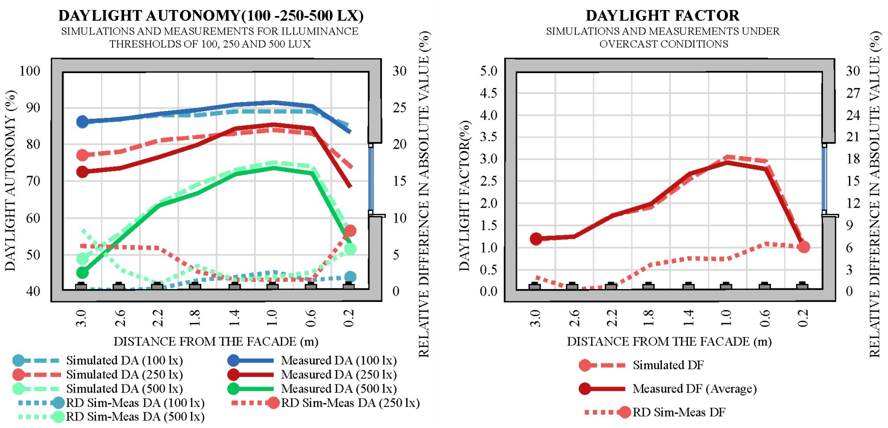

Figure 4: Daylight Autonomy (DA) and Daylight Factor (DF) results generated from illuminance measurements and simulation calculations

DA values calculated from simulations are close to those performed from measurements, with an average relative difference of 1.00% and the highest maximum deviation obtained for the 500 lux threshold (8.4%). It should also be noted that the divergences between simulations and measurement are greater in terms of depth for all of the illuminance thresholds under study, but are therefore acceptable for this validation study as low values under 10%.

Divergences in DF results are lower than those observed for DA, with an average relative difference of 0.96% and showing the highest deviations (4.5 to 6.5%) at the control points closest to the window. As in the previous analysis, these deviations are acceptable, given that they are below 10%.

From these results it can be deduced that Daysim 3.1 properly calculates DA and DF metrics in rooms with similar boundary conditions, and is a suitable tool for linking static and dynamic metrics to DAm.

3. Results

3.1. Relationship with daylight factors

As explained in the calculation procedure of DAm, interior illuminance can be quantified knowing the DF at a given point and the external illuminance under overcast sky conditions. The external illuminance can be deduced from equation (8), expressed above, which depends on the solar altitude, defined in (5) and the luminance measured at the zenith of the sky vault, seen in (6). Accordingly, external illuminance varies depending on latitude and solar time, which can be bounded by occupancy hours.

It should be noted that vertical illuminance plays an important role in high latitudes locations, in many situations with greater influence than horizontal one. However, DF is defined as the ratio of interior to exterior illuminance, measured on a horizontal work plane [CIE 2011] and most of the calculation programs define this metric following this definition.

Once the external illuminance is deduced according to latitude and occupancy hours, the daylight illuminance, measured at an inner point, can be determined following the DF value at the studied point. Thus, the percentage of the occupied time during the year when an illuminance threshold is achieved can be easily calculated, determining the value of DAm. Following this statement, Tables 2 to 6 show the relationship between DAm and DF, in accordance with the latitude and the occupancy hours, which determine the solar altitude and therefore the external illuminance. Each table represents DAm values for a certain illuminance threshold, varying from 100 to 500 lx.

Table 2: Minimum daylight autonomy according to a threshold of 100 lux and occupancy hours from 8 am to 5 pm.

Daylight Factor	Latitude												
	0 °	5 °	10 °	15 °	20 °	25 °	30 °	35 °	40 °	45 °	50 °	55 °	60 °
1.0%	70%	66%	65%	63%	60%	56%	48%	43%	38%	34%	30%	25%	21%
1.5%	79%	79%	78%	77%	76%	72%	69%	64%	57%	51%	45%	41%	37%
2.0%	84%	84%	82%	80%	79%	79%	77%	74%	70%	63%	56%	50%	46%
2.5%	85%	84%	85%	86%	84%	83%	82%	79%	76%	71%	63%	57%	52%
3.0%	87%	88%	90%	89%	89%	85%	84%	83%	79%	77%	71%	62%	56%
3.5%	90%	91%	90%	90%	90%	88%	85%	84%	83%	80%	75%	66%	60%
4.0%	92%	92%	91%	91%	90%	90%	87%	86%	85%	82%	78%	70%	62%
4.5%	93%	92%	92%	91%	90%	90%	89%	87%	86%	83%	81%	73%	64%
5.0%	94%	93%	92%	91%	91%	90%	91%	89%	87%	85%	82%	76%	66%

Table 3: Minimum daylight autonomy according to a threshold of 200 lux and occupancy hours from 8 am to 5 pm.

Daylight Factor	Latitude												
	0 °	5 °	10 °	15 °	20 °	25 °	30 °	35 °	40 °	45 °	50 °	55 °	60 °
1.0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
1.5%	50%	47%	45%	40%	35%	31%	27%	24%	21%	17%	14%	9%	4%
2.0%	70%	66%	65%	63%	60%	56%	48%	43%	38%	34%	30%	25%	21%
2.5%	73%	71%	71%	70%	68%	67%	62%	56%	49%	44%	39%	35%	30%
3.0%	79%	79%	78%	77%	76%	72%	69%	64%	57%	51%	45%	41%	37%
3.5%	84%	82%	80%	79%	78%	77%	72%	71%	66%	57%	52%	47%	42%
4.0%	84%	84%	82%	80%	79%	79%	77%	74%	70%	63%	56%	50%	46%
4.5%	84%	84%	84%	82%	82%	81%	81%	77%	74%	69%	59%	53%	49%
5.0%	85%	84%	85%	86%	84%	83%	82%	79%	76%	71%	63%	57%	52%

Table 4: Minimum daylight autonomy according to a threshold of 300 lux and occupancy hours from 8 am to 5 pm.

Daylight Factor	Latitude												
	0 °	5 °	10 °	15 °	20 °	25 °	30 °	35 °	40 °	45 °	50 °	55 °	60 °
1.0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
1.5%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
2.0%	37%	37%	35%	31%	28%	24%	21%	18%	14%	9%	6%	1%	0%
2.5%	53%	53%	53%	52%	48%	42%	37%	33%	29%	25%	20%	15%	10%
3.0%	70%	66%	65%	63%	60%	56%	48%	43%	38%	34%	30%	25%	21%
3.5%	70%	70%	69%	66%	66%	64%	60%	52%	46%	41%	37%	32%	28%
4.0%	74%	75%	76%	75%	71%	69%	65%	60%	52%	47%	42%	37%	33%
4.5%	79%	79%	78%	77%	76%	72%	69%	64%	57%	51%	45%	41%	37%
5.0%	83%	81%	79%	78%	77%	75%	71%	68%	64%	55%	50%	45%	40%

Table 5: Minimum daylight autonomy according to a threshold of 400 lux and occupancy hours from 8 am to 5 pm.

Daylight Factor	Latitude												
	0 °	5 °	10 °	15 °	20 °	25 °	30 °	35 °	40 °	45 °	50 °	55 °	60 °
1.0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
1.5%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
2.0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
2.5%	27%	24%	21%	19%	18%	17%	14%	11%	8%	5%	1%	0%	0%
3.0%	50%	47%	45%	40%	35%	31%	27%	24%	21%	17%	14%	9%	4%
3.5%	57%	59%	61%	57%	54%	46%	41%	36%	32%	28%	23%	18%	12%
4.0%	70%	66%	65%	63%	60%	56%	48%	43%	38%	34%	30%	25%	21%
4.5%	70%	70%	68%	65%	64%	61%	57%	50%	45%	40%	35%	31%	26%
5.0%	73%	71%	71%	70%	68%	67%	62%	56%	49%	44%	39%	35%	30%

Table 6: Minimum daylight autonomy according to a threshold of 500 lux and occupancy hours from 8 am to 5 pm.

Daylight Factor	Latitude												
	0 °	5 °	10 °	15 °	20 °	25 °	30 °	35 °	40 °	45 °	50 °	55 °	60 °
1.0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
1.5%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
2.0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
2.5%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
3.0%	21%	21%	19%	17%	15%	13%	11%	9%	6%	1%	0%	0%	0%

3.5%	42%	44%	40%	35%	31%	27%	24%	21%	17%	14%	8%	4%	0%
4.0%	51%	50%	46%	46%	42%	38%	34%	30%	26%	21%	17%	13%	8%
4.5%	60%	62%	62%	59%	55%	48%	42%	38%	33%	29%	25%	20%	14%
5.0%	70%	66%	65%	63%	60%	56%	48%	43%	38%	34%	30%	25%	21%

Unlike other dynamic metrics such as DA or UDI, the values shown in Tables 2 to 6 can be applied broadly. As expected, the variation in occupancy hours affects the range of solar altitude, so that the interior illuminance and therefore the calculation of DAm also vary.

It is worth noting that, as deduced from equation (10), DAm can be directly calculated for a certain DF value, regardless of the angle of the plane where the study point is located. Therefore, DAm can be measured in a vertical plane and its correlation with DF would be the same, corresponding to values shown in Tables 2 to 6. This could be particularly useful for determining vertical illuminances, to calculate the impact of lighting on the human circadian response.

According to occupancy hours from 9 am to 5 pm, the DAm values increase between 7 and 11% compared to a schedule from 8 am to 5 pm. In the case of a time frame from 10 am to 5 pm, the DAm values rise up to 25% compared to the values shown in Tables 2 to 6. If the closing hour varies, from 5 pm to 3 pm, the DAm calculation is barely affected, since the luminance of the sky vault is sufficient to promote a minimum illuminance threshold during the afternoon.

3.2. Relationship with daylight autonomy

3.2.1. Calculation methodology

Daysim 3.1 is used to find a link between DAm and the dynamic metrics mentioned above. As previously deduced, this tool calculates both DF and DA values accurately, and can therefore determine the relationship between the concepts above and the proposed metric. The calculation parameters of the simulation program are defined in the previous section on validation using dynamic metrics and are shown in Table 1.

A virtual room was used to quantify the dynamic metrics according to the geometry of the window and the distance from the facade. The venue is 3.0 m wide by 6.0 m deep by 3.0 m high, corresponding to the typical dimensions of a small office or a living room. A window of variable size is located in the facade, with a visible transmission of 0.7. The opening size corresponds to a small or large window (opening to facade ratio of 20 and 40% respectively) and the jambs, lintel and sill are 0.25 m thick. The inner surfaces of the room act as Lambertian reflectors, so that the luminance reflected is directly proportional to the cosine of the angle between the observer's line of sight and the surface normal. The reflectance values for each surface are described in Figure 5.

The DA values are measured on a central axis considering a spacing of 0.30 m between study points and a height of 0.60 m above the floor, as shown in Figure 5. Subsequently, the DAm values can be deduced from the DF results defined for each point analyzed, following the calculation procedure described above.

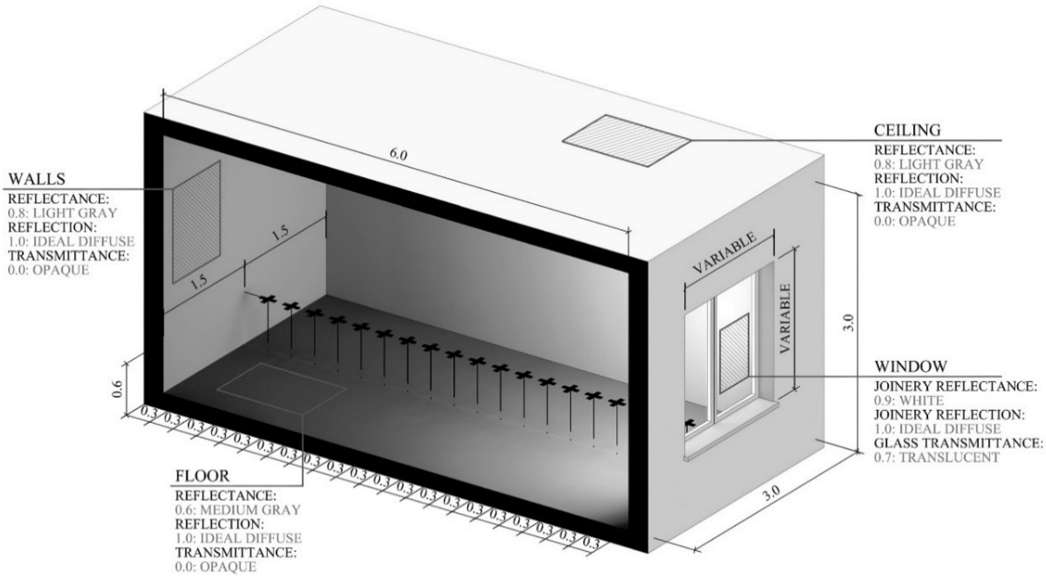

Figure 5: Description of the calculation model for determining the relationship between dynamic metrics.

The illuminance threshold defined for calculating the DA in this study is 250 lux, a sufficient amount to carry out the most common tasks in a residential space. The occupancy hours considered in this trial are from 8.00 am to 5.00 pm, corresponding to a typical use of daylighting.

Four locations are studied for this research in order to quantify the variation in DA values depending on different weather conditions. The first location corresponds to London, UK, at 50° north latitude with mainly overcast skies. The second location is Madrid, Spain, at 40° north latitude with predominantly clear skies. The third and fourth sets of weather conditions correspond to Stockholm, Sweden, close to 60° north latitude and Munich, Germany, near 50° north latitude with mainly intermediate skies.

In addition, four orientations are considered for the window in order to assess the effect of the orientation of the opening in the quantification of DA and its relationship with DAm. The orientations studied are north, east, south and west.

3.2.2. Relationship according to room location

Following the methodology described above, Figure 6 shows DA and DAm values for the calculation model, according to the latitude and weather data of four locations: London (LON), Madrid (MAD), Stockholm (STO) and Munich (MUN), considering two window sizes (window to facade ratio of 20 and 40%) and a north-oriented opening.

As expected, DAm values for the room sections shown in Figure 6 are almost always below DA values, except in the zone near the facade, where both metrics tend to converge. As can be deduced from the variations of luminance between clear and overcast skies, DAm values could be higher than DA measures in certain circumstances, usually in the zone near the façade for windows facing north.

DAm values are null for a distance greater than 3.6 m from the facade in the case of small windows (ratio of 20%) and under 20% for 5.1 m in the room model with a larger window (ratio of 40%), that is to say, DAm reaches approximately twice the height of the window lintel.

According to the results observed in Figure 6, equation (11) shows the relationship of the dynamic metrics analyzed, depending on the variables not considered in the calculation of DAm, those of weather conditions:

$$DA = DA_m + (1 - DA_m) \cdot L_F \cdot d^{0.25} \quad (11)$$

where *DAm* is the minimum daylight autonomy deduced from DF, L_F is the location factor, which depends on the average weather conditions and *d* is the distance in m between the point studied and the facade.

The predictive method described in equation (11) is derived by a curve fitting procedure, comparing the results of DA and DAm and deducting the weighting factors to provide the minimum value for the average error and for the standard deviation. As can be deduced, the method proposed is therefore limited to the specific situations analyzed, so it can be improved by means of complementary calculations carried out under different contexts. Accordingly, the modification of the weighting factors proposed, as well as the addition of new factors linked to other variables (such as window shape, shading devices or external obstructions), can be determined in further research. It should be noted that these weighting factors would also change in the case of the correlation of DA and DAm for vertical planes.

The location factor varies between 0.00 (continuous overcast sky) and 1.00 (continuous clear sky) depending on the climate conditions of the location analyzed. Table 7 shows the location factor L_F considered for the rooms studied:

Table 7: Location factor L_F for the rooms studied according to the average weather conditions.

Location	Location Factor
Madrid	0.50
Munich	0.45
Stockholm	0.40
London	0.30

Future developments may aims toward formulating an accurate link between L_F and the weather data files which define the global and diffuse irradiances [LBNL 2012].

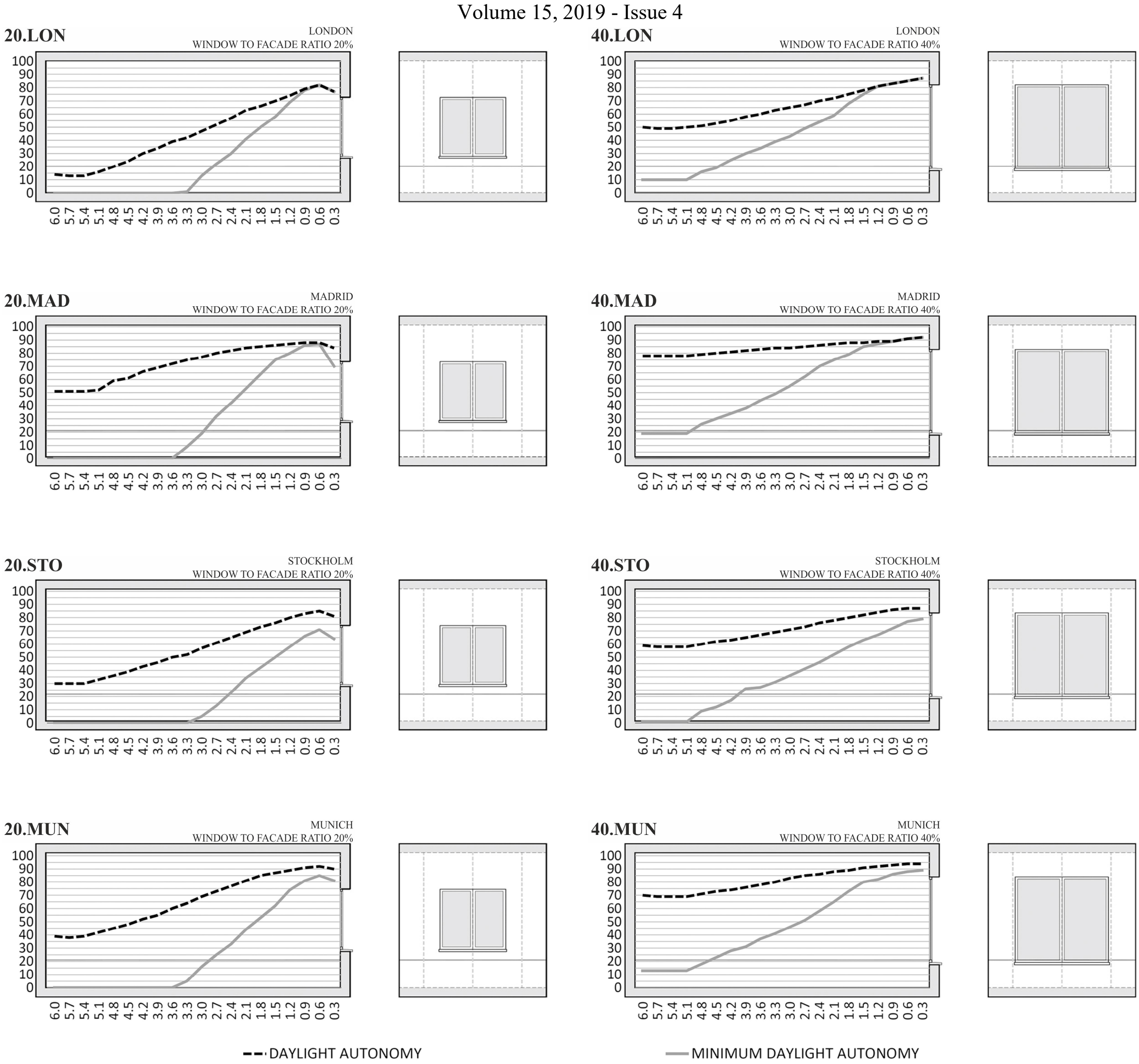

Figure 6: Daylight Autonomy (DA) and Minimum Daylight Autonomy (DAm) for calculation model according to room location.

Figures 7 to 10 represent the DA values defined by the simulation program and those determined by the predictive method described in equation (11), for the locations studied described above and the L_F factors shown in Table 7. Solid lines show the results obtained by means of Daysim 3.1, while dashed lines represent the quantification of the expression (11), depending on the distance from the facade. Moreover, red lines describe the metric results for large openings (ratio of 40%) and blue lines express the DA values for small windows (ratio of 20%). The comparison of both methods has been carried out for positive values of DAm. The relative difference between both methods is quantified in the secondary axis.

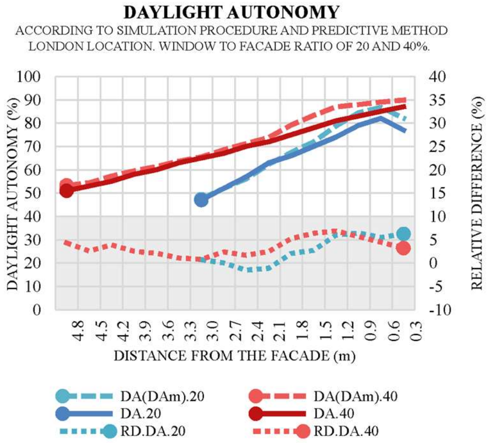

Figure 7: Daylight Autonomy (DA) quantified according to simulation and predictive method for London location and relative difference between both procedures.

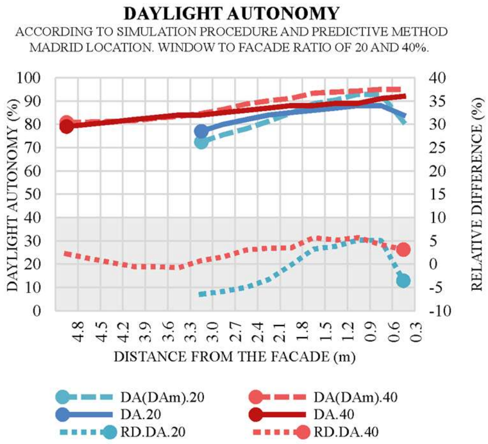

Figure 8: Daylight Autonomy (DA) quantified according to simulation and predictive method for Madrid location and relative difference between both procedures.

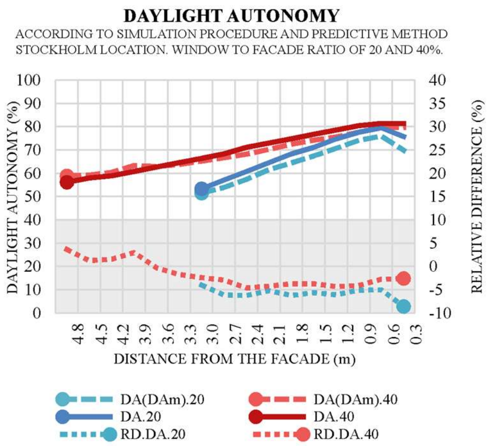

Figure 9: Daylight Autonomy (DA) quantified according to simulation and predictive method for Stockholm location and relative difference between both procedures.

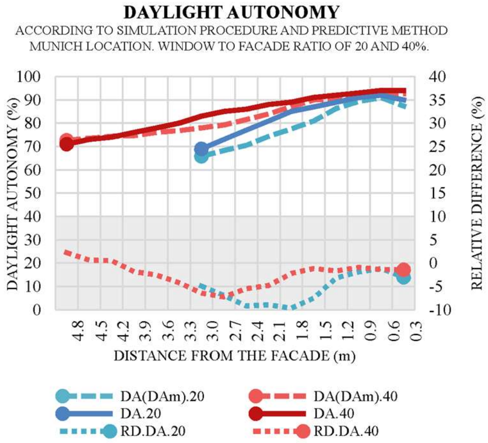

Figure 10: Daylight Autonomy (DA) quantified according to simulation and predictive method for Munich location and relative difference between both procedures.

As deduced from Figures 7 to 10, the predictive method achieves noticeable accuracy for determining the DA values depending on the DAm calculation, showing a divergence below 10% for all cases compared to the results of the simulation program. In the case of the London location, shown in Figure 7, the average relative difference is 3.4%, with a maximum value of 6.9%. As deduced from Figure 8, the predictive method can determine the DA values for Madrid with an average relative difference of 3.2% and a maximum divergence of 6.5% compared to the simulation program. This margin of error is slightly higher for the cases of Stockholm and Munich, described in Figures 9 and 10 respectively, which show an average relative difference of 3.9% for both locations.

3.3.3. Relationship according to window orientation

As in the previous trial, Figure 11 shows DA and DAm values for the room model defined in the methodology, according to the orientation of the window: north (N), east (E), south (S) and west (W), depending on two window sizes (window to facade ratio of 20 and 40%) and considering the London location as an case. Other studied locations are not shown for the sake of brevity.

As in the previous trial and as seen in Figure 11, the room sections show a DAm value almost always lower than the DA measurements quantified using the simulation program, converging in the zone near the facade. Since DAm is calculated according to overcast sky conditions, the window orientation does not affect the results of this metric. As concluded above, DAm values reach twice the height of the window lintel, defining the minimum area of the room where the illuminance threshold is met under a constant cloudy scenario.

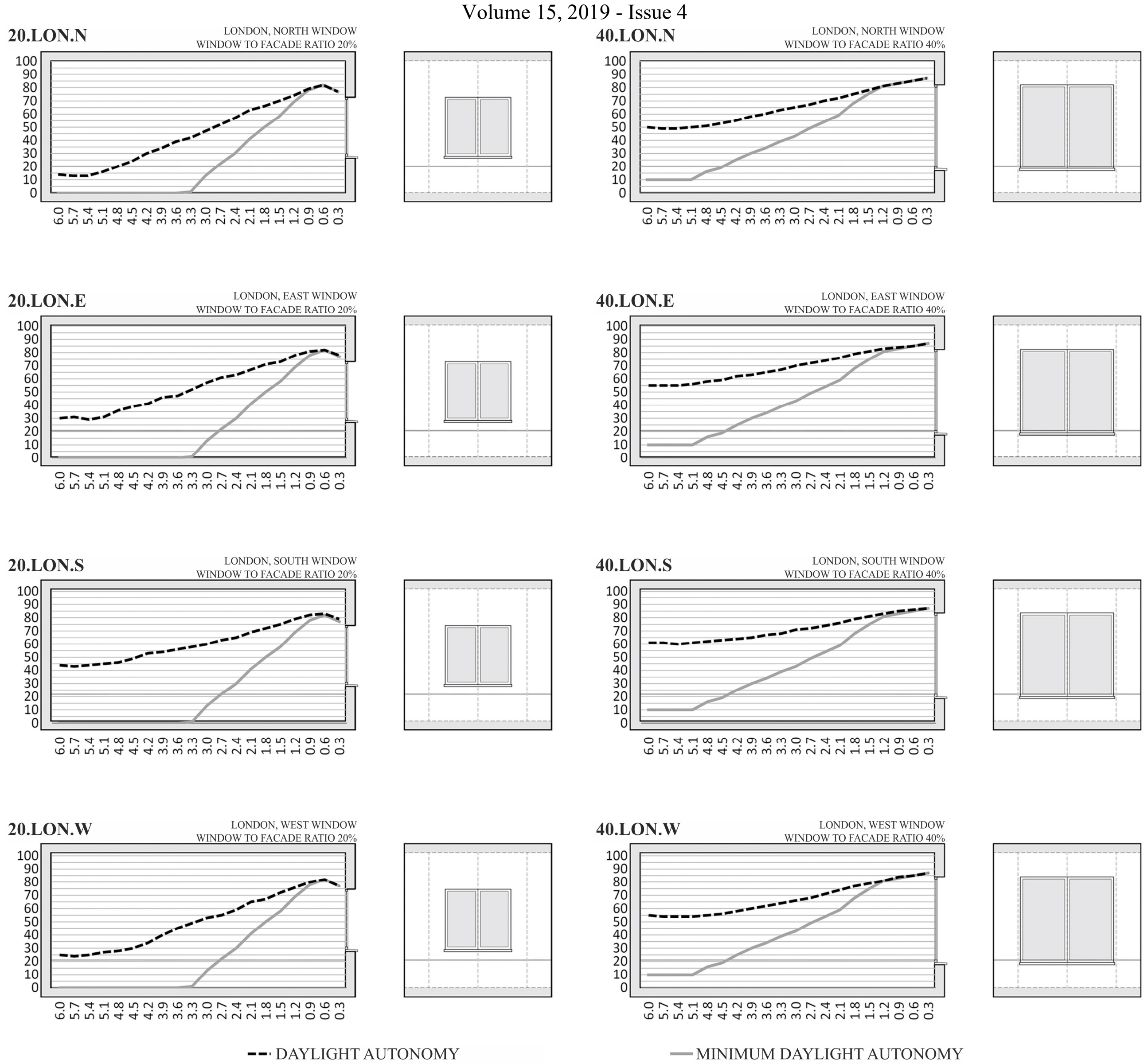

Figure 11: Daylight Autonomy (DA) and Minimum Daylight Autonomy (DAm) for calculation model according to window orientation for London location.

As deduced from the measurements shown in Figure 11, equation (12) represents the relationship of DA and DAm according to weather conditions and the influence of the window orientation:

$$DA = DA_M + (1 - DA_M) \cdot L_F \cdot O_F \cdot d^{0.25} \ (12)$$

where *DAm* is the minimum daylight autonomy deduced from DF, L_F is the location factor, O_F is the orientation factor and *d* is the distance in m between the point studied and the facade.

The orientation factor ranges from 1.00 (north orientation) to 1.25 (south orientation) depending on the orientation of the window. As in the case above, the deduction of these weighting factors have been carried out by means of a curve fitting procedure, determining each factor for the minimum average error. The improvement of the weighting factors proposed, as well as the determination of new parameters linked to other daylight conditions, can be defined in further research. Table 8 shows the orientation factor O_F deduced from the calculation results:

Table 8: Orientation factor O_F for the rooms studied according to the orientation of the window.

Orientation	Orientation Factor
North	1.00
East	1.15
South	1.25
West	1.15

As seen before in the analysis of room location, Figures 12 to 15 show the DA values quantified by the simulation program and those predicted by equation (12), based on the analysis of the window orientation and the weight factor described in Table 8. As in the previous graphs, solid lines represent the results of Daysim 3.1, while dashed lines describe the measurements of the method proposed in (12) depending on the distance from the facade. As seen above, the divergence between both procedures is quantified in the secondary axis.

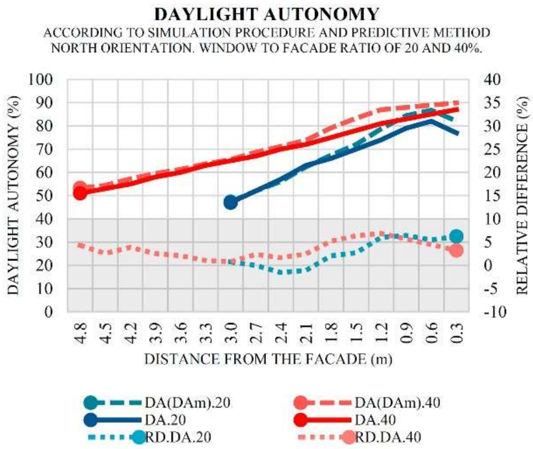

Figure 12: Daylight Autonomy (DA) quantified according to simulation and predictive method for north orientation and relative difference between both procedures.

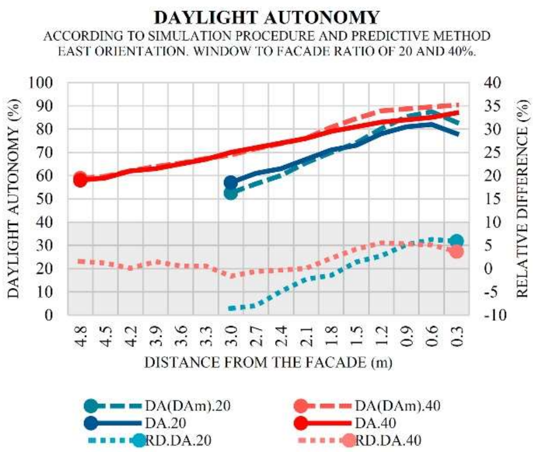

Figure 13: Daylight Autonomy (DA) quantified according to simulation and predictive method for east orientation and relative difference between both procedures.

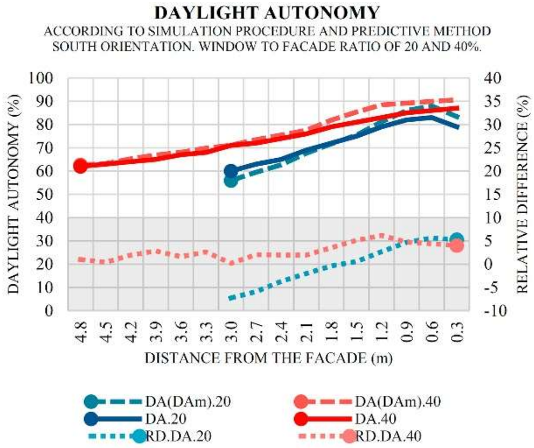

Figure 14: Daylight Autonomy (DA) quantified according to simulation and predictive method for south orientation and relative difference between both procedures.

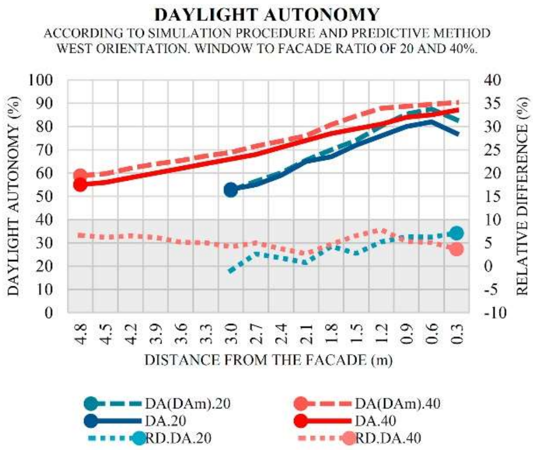

Figure 15: Daylight Autonomy (DA) quantified according to simulation and predictive method for west orientation and relative difference between both procedures.

As seen in Figures 12 to 15, the method proposed also provides a proper fit when calculating the DA values based on the DAm calculation, demonstrating a divergence lower than 10% for all case studies compared to the simulation program. As concluded for the north orientation described in Figure 12, the average relative difference is 3.4%, while the maximum divergence is 6.8%. In the case of east and west orientations, shown in Figures 13 and 15 respectively, the average difference is about 3.9%, while this divergence is slightly lower for south orientation, as seen in Figure 14.

As can be deduced, the factors defined for the window orientation are limited by the occupancy hours described in the methodology, so that the weight values defined in Table 8 could be adjusted for other schedules. Moreover, the location factors concluded above can be modified for other weather conditions not considered in this study. Based on the previous statements, a deeper analysis of the weighting factors could be carried out in a future research, in order to provide new nuances for other scenarios. In any case, these factors are an initial approach to determining a relationship between DAm and the dynamic metrics mentioned above, and therefore are a useful tool for designers.

4. Conclusions

As discussed in the background, daylight metrics are a useful tool for determining the performance of an architectural space in order to provide suitable natural light and energy saving in electric lighting. However, static metrics such as DF do not provide a reliable quantification of energy consumption in electric lighting, since these concepts ignore the illuminance requirements and weather conditions of the location studied. Moreover, dynamic metrics, most notably DA, provide a suitable calculation of energy savings, considering all the variables which affect the illuminance thresholds, although the calculation is really complex and not linked in any way to the most widespread static metrics.

According to the previous scenario, DAm provides a reliable relationship between classic and new daylight metrics by means of tables and predictive procedures, easily quantifying the DF and DA values. Moreover, DAm represents the maximum energy consumption which can be produced by an electric lighting facility, assuming an ideal on/off lighting control, since it calculates the percentage of the occupied time throughout the year when an illuminance threshold is achieved under a continuous overcast sky, despite the fact that in certain circumstances clear skies may represent a worse scenario. In addition, this new concept can be calculated following the simple procedure explained above, so that the entire calculation process can be included in a spreadsheet, if DF values are provided either from measurements or simulation.

As deduced from the analysis of the relationship between DAm and static metrics, when the DF at a given point and the external illuminance under overcast sky conditions are known, the interior illuminance can easily be quantified depending on time. Therefore, in accordance with the previous variables and defining an illuminance threshold, DAm can be calculated exactly, since both metrics mentioned are based on the same climate conditions. This can be useful for deducing the minimum energy savings according to DF measurements (considering a suitable light flux management system), without needing to use dynamic metrics for analysis. Tables 2 to 6 show examples of the DAm values which correspond to DF, depending on the latitude (which determines the solar altitude), the occupancy hours and the illuminance threshold.

As seen in the analysis of the relationship between DAm and dynamic metrics, equation (12), shown above, represents the link between DA and DAm according to the weather conditions and the influence of the window orientation. The formulation mentioned above describes the resulting DA values based on DAm calculation and two weight factors relating to the location and the orientation of the window. Therefore, equation (12) can serve to determine the relationship between DA and DF, applying this formula to the DAm values shown in Tables 2 to 6. The formula proposed achieves noticeable accuracy when predicting DA measurements according to weather conditions, as deduced from Figures 7 to 10, where a maximum divergence below 10%

is observed. Moreover, the method defined is also highly precise when determining the DA values depending on window orientation, as seen in Figures 12 to 15. Specifically, the predictive method provides a maximum relative difference lower than 10% compared to the results observed using the calculation program, considering the case study of different window orientations. Analyzing all scenarios relating to room location and window orientation, the average divergence of the proposed equation and the results observed from Daysim 3.1 does not exceed 3.9%. It should be noted that the accuracy of the simulation program calculating both DA and DF metrics has been previously tested with a real model under real conditions, based on a room with similar dimensions and characteristics, so that the results provided by the method proposed could be extrapolated to a real scenario. Accordingly, it can be concluded that the predictive method developed in this research provides a reliable calculation of DA measurements based on the DAm estimations, using a suitable procedure to deduce the dynamic metrics in accordance with the DF values. As described above, the weighting factors of the method proposed are limited to the boundary conditions of the scenario studied, although they serve as an initial approach to link static and dynamic metrics. The suitable quantification of the weighting factors requires further research in which all the variables that affect daylight metrics have been considered, such as the window shape, the external environment and extreme latitudes and climate conditions.

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