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Contribution of the Measurement Uncertainty of the Daylight Factor in Buildings for the Comparison of Experimental Methods

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Abstract – **Lighting has a major role to environmental comfort and energy efficiency in buildings, being related to parameters that establish comfortable visual environment suitable for the execution of visual tasks. The lighting of interior spaces can be accomplished using natural light, artificial light or, preferably, using a combination of the two. The measurement of Daylight Factor (DF) is required as a quantity to characterize the indoor luminous environment in buildings.**

The measurement of lighting conditions is usually carried out taking into account the recommendations and the reference illuminance levels contained in Standards EN 12464-1 [1], providing the conditions to indoor electric lighting, and EN 17037 [2], providing the framework of daylight in buildings, being still under evaluation to accomplish a wide variety of real scenarios. Although the characterization of artificial lighting conditions is relatively common, the systematic "in situ" assessment of daylighting conditions still has to solve the differences arising from the use of different available methods and the impact of external obstructions in the accuracy, and the suitability of the experimental approaches. In this paper, the evaluation of measurement uncertainty related with the Daylight Factor, obtained using four different experimental methods is developed and a comparison of the accuracy of the methods results is given, providing a tool to validation and to support decision-making processes.

Keywords – Daylighting; daylight factor; buildings; measurement uncertainty

I. INTRODUCTION

Lighting is unquestionably one of the aspects that most contributes to environmental comfort and energy efficiency, being one of the main conditioning factors of environmental quality inside buildings. Its main function is to provide a comfortable visual environment suitable for the execution of visual tasks. The lighting of interior spaces can be accomplished using natural light, artificial light or, preferably, using a combination of the two. The characterization of the indoor environmental quality in buildings requires the measurement of several quantities, being the Daylight Factor (*DF*) the most common parameter used to characterize the indoor luminous environment in buildings. The Daylight Factor (expressed in %) is defined as [1]: "Ratio, in percentage, between the illuminance at a point on a given plane, due to the natural light received directly or indirectly from a sky, whose luminance distribution is assumed or known, and the illuminance on a horizontal plane due to an unobstructed hemisphere of that sky. Direct sunlight is excluded from both illuminance values".

The measurement of lighting conditions is usually carried out taking into account the recommendations and the reference illuminance levels of EN 12464-1 [1], which provides a general guidance for the assessment of daylighting conditions in buildings, mainly focus in indoor electric lighting conditions, and of EN 17037 [2], providing the framework of daylight in buildings, the last one being still under evaluation to accomplish the wide variety of real scenarios.

Although the characterization of artificial lighting conditions is relatively common, the systematic "in situ" assessment of daylighting conditions still has to solve the differences arising from the use of different available methods and the impact of external obstructions in the accuracy, and the suitability of the experimental approaches. In this paper, the evaluation of measurement uncertainty related with the Daylight Factor, obtained using four different experimental methods is developed and a comparison of the accuracy of the methods results is given, providing a tool to support decision-making processes. This approach is required to have an informative selection and validation of the methods and for the definition of decision rules for conformity assessment [3,4,5] based on the standards above mentioned.

II. DAYLIGHT FACTOR TESTING METHODS

It is usual to distinguish the quantitative aspects from the qualitative aspects of both daylighting and electric lighting, although both are complementary in terms of obtaining an adequate interior light environment. The quantitative aspects of lighting are, essentially, related to the values of the illuminances available at work planes, while the qualitative aspects have essentially to do with the factors that contribute to the overall feeling of visual comfort of the occupants and with the main monitoring procedures, in order to characterize the quantitative aspects of natural lighting, including: the measurement of the *DF* over the main work planes (for overcast conditions); and the measurement of illuminance at certain points representative of the spaces (for overcast and clear sky conditions).

The validity of the *DF* concept, especially with regards to its measurement under all types of sky conditions, is still a subject of discussion today [6,7,8,9]. The advantage of the *DF* over other types of approaches is that it allows the calculation and/or measurement of a parameter that can be used to assess the daylight performance of a room or space, in the worst nebulosity situation possible. However, the measurement of the *DF* "under real sky conditions", involves significant experimental errors, essentially due to the deviations of the overcast sky luminance distribution, under which measurements are made, in relation to the standard theoretical CIE Overcast Sky model. There are different methods used for the measurement of *DF*, being described a conventional approach and three alternatives.

Method 1 – conventional approach

The usual method of measuring the *DF* involves the use of two illuminance sensors, one located at a measurement point inside a room, and the other, placed horizontally outside the building under an unobstructed sky hemisphere, as shown in Figure 1.

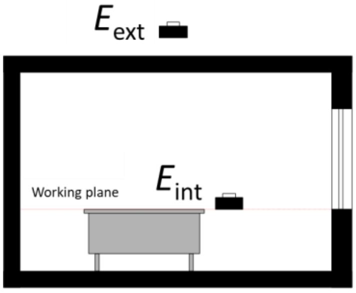

Figure 1. Illustration of the conventional method for DF measurement.

The *DF* (in %) for a point on a (working) plane is then the ratio between the interior illuminance measured at that point (E_{int}) and the simultaneous unobstructed horizontal exterior illuminance (E_{ext}) as given in equation (1), being both measured simultaneously under standard overcast conditions:

$$DF(\%) = \left[\frac{E_{int}}{E_{ext}}\right] \cdot 100. \qquad (1)$$

When measuring illuminances, overcast conditions must be continuously checked, ensuring that they are close to a standard overcast sky, so that measurements are reproducible. This method is in accordance with the CIE's definition of *DF*.

Method 2

The first of the alternative methods consists in using a semi-blocked external sensor in order to receive daylight from only half of the hemisphere, as seen in Figure 2.

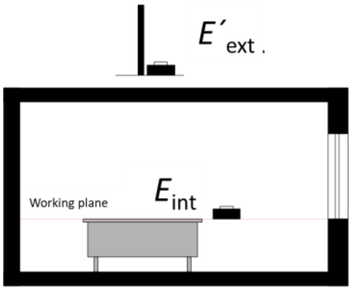

Figure 2. Alternative DF measurement method, being the outer sensor clogged so as to "see" only half of the sky's hemisphere.

Naturally, the visible sky hemisphere should be the one that most contributes to the interior illuminances. To obtain the *DF* value, the quotient between the interior and exterior illuminances must be multiplied by 0.5, i.e.

$$DF(\%) = \left[\frac{E_{int}}{E'_{ext}} \cdot 0.5\right] \cdot 100. \qquad (2)$$

The obstructing "screen" should be matt and black (in order to avoid spurious reflections) and its dimensions should be about an order of magnitude larger than the size of the sensor's sensitive area. As in the traditional method, E'_{ext} and E_{int} are measured simultaneously under standard overcast conditions and the visible sky hemisphere should be unobstructed.

Method 3

The third method consists in replacing the measurement of the horizontal exterior illuminance by a vertical illuminance, using a sensor placed vertically on the outer face of the window and, simultaneously, obstructing it from the light reflected by the ground, as seen in Figure 3.

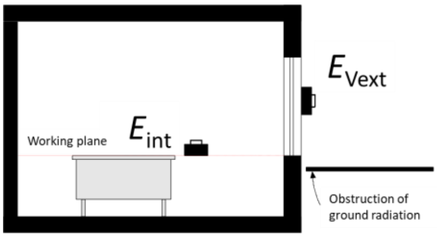

Figure 3. Method 3 for DF measurement, being the outer sensor being obstructed from light reflected by the ground.

Again, the obstructing screen must be matt black, at least 10 times larger than the photosensitive cell sensor and should be placed as close as possible to the sensor without obstructing the window, as shown in Figure 3. E_{Vext} and E_{int} should be measured simultaneously under standard overcast conditions and the visible sky semi-hemisphere should be unobstructed. For a CIE Standard Overcast Sky, the relationship between vertical illuminance (E_V) and horizontal illuminance (E_H), due to an overcast and unobstructed sky hemisphere, is $E_V = 0.396\,E_H$. Thus, using this method, the *DF* will be given by the following expression [6]:

$$DF(\%) = \left[\frac{E_{int}}{E_{Vext}} \cdot 0.396\right] \cdot 100 \qquad (3)$$

In the two previous methods, the external sensors should be blocked by relatively large black matt screens (at least 10 times larger than the diameter of the sensor cell). The accuracy of both methods increase with increasing luminance distribution deviation from the CIE Standard Overcast Sky Luminance distribution.

Method 4

Another alternative method of measuring and calculating the *DF* [10] consists in replacing the measurement of the exterior horizontal illuminance with the measurement of luminance in front of an open window with an inclination of 42º in relation to the horizon (see Figure 4).

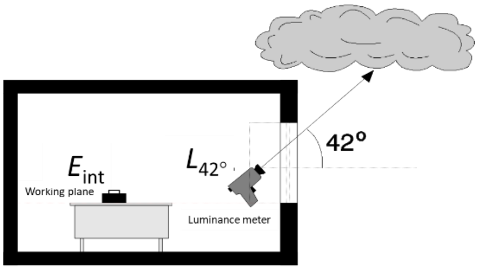

Figure 4. Method 4 for alternative DF measurement using the measurement of luminance.

In this case, equation (4) can be applied,

$$E_{\text{ext}} = L_{42°} \cdot \pi \tag{4}$$

and *DF* is calculated as follows:

$$DF(\%) = \left[\frac{E_{int}}{L_{42°} \cdot \pi}\right] \cdot 100 \tag{5}$$

The luminance is measured at an angle of 42º in relation to the horizon because, under a CIE Standard Overcast Sky, the unobstructed horizontal illuminance (expressed in lux) is equal to the value of that luminance (in cd/m^2) multiplied by π [10].

This method is particularly suitable for situations in which there are significant external obstructions, but it can lead to significant errors if there are large spatial variations in the luminance of the sky, and should not be used if the nebulosity has clearly visible dark and light areas. The accuracy of the method can be improved using a wide aperture luminance meter (10º, for example) in order to be able to obtain a significant and representative sky "sample" for the measurement.

In regions where non-overcast skies prevail, the question of the validity of the *DF* measurement under conditions that deviate significantly from the assumed nebulosity conditions of the CIE Standard Overcast Sky is of decisive importance. The traditional method is the most rigorous and reliable, as long as it is possible to carry out the external measurements in a suitable place, free from significant obstructions. Otherwise, one of the alternative methods mentioned can be used.

The intended use of these methods is to obtain 2D distributions and profiles of the Daylight Factor (*DF*) at indoor spaces, requiring experimental procedures usually developed in three stages:

- the first stage requires to be able to obtain pairs of values of illuminance, inside the indoor place and outside according with the specifications of each method, in order to evaluate the *DF* measurand;
- the second stage requires to define a grid of measurable points in a 2D surface representative of the indoor place under evaluation, and use the measurement data to define isolines and the related 2D distribution; and
- The third stage is intended to obtain profiles of *DF* for planes orthogonal to the 2D surface of glazed interfaces.

This study will focus on the measurement quality related with the measurement of illuminance for a single pair of measurements and the propagation of uncertainty to the determination of *DF* for the methods referred. Further studies intend to obtain the propagation of uncertainty for stages 2 and 3.

In the comparison proposed method 4 was not considered intentionally because this method has specific characteristics that are distinguished from the other methods. In particular, the fact that it uses an indirect mathematical relationship between the luminance and illuminance quantities, thus requiring an evaluation of the process as a multistage mathematical model. In the specific case, the common component of uncertainty associated with the measurement of illuminance observed in the other methods should have in method 4 a different evaluation approach, resulting from the use of another type of measuring equipment, with different traceability and sources of uncertainty, and should not, therefore, be compared in this context but comparable in a perspective of different *DF* measurement principles.

III. EVALUATION OF MEASUREMENT UNCERTAINTY OF ILLUMINANCE USING PHOTOMETRIC SENSORS

The International Lighting Commission (CIE) provides recommendations regarding the technical specifications of the illuminance meters to use in the daylight measurements and the [11] calibration methods to apply. To obtain the measurement uncertainty related to the methods described, a first step needed is to evaluate the measurement uncertainty of the measuring instruments, in this case, the photometric sensors and associated chains. This is called the *instrumental measurement uncertainty* and defined in the International Vocabulary of Metrology [12] as the *uncertainty component of measurement uncertainty arising from a measuring instrument or measuring system in use*.

Table 1. Error sources of photometric sensors, variation estimates and PDF´s used for uncertainty evaluation [14]

Error source (instrumental)	Variation / %	PDF
Calibration errors	5% max.	Normal
Relative spectral response	5%	Uniform
Spatial (cosine)	2%	Uniform
Angular and azimuth	1%	Uniform
Displacement	0%	---
Tilt	0.5%	Normal
Linearity	0.5%	Normal
Fatigue	0%	---
Temperature coefficient*	1%	Uniform
Response time	0%	---
Long-term stability	2% / year	Uniform
Immersion effect	0%	---
Surface variation	0%	---
Readout	1%	Uniform
Repeatability	0.5%	Normal

* Related to a temperature variation of 10 ºC.

The approach for this evaluation applies the procedure describe in the GUM [13] which requires to identify the instrumental sources of error [14], to quantify it in terms of variation, establishing appropriate probability distribution functions (PDF's found in Table 1) and to use the GUM Law of Propagation of Uncertainty to obtain the standard-measurement uncertainty and 95% expanded measurement uncertainty.

In this case, a linear model approach (6) is consistent with the measurement, enabling to achieve a proper estimate of the output measurand, although some sources of error have a nonlinear functional behaviour. In these cases, linearization allows to obtain a linear contribution for the measurement uncertainty. Thus, the functional relation can be written as:

$$E = E_{\mathrm{o}} + \delta E_{\mathrm{cal}} + \delta E_i \qquad (6)$$

being E the measurement result, E_{o}, the reading, δE_{cal}, the correction due to the photometric instrument calibration and δE_i, the (average) corrections due to the sources of error identified.

Using equation (6) and the GUM Law of Propagation of uncertainty, considering that there are no correlations between the input quantities, the evaluation of the standard uncertainty of the measurand, E, can be calculated by:

$$u^2(E) = \left(\frac{\partial E}{\partial E_{\mathrm{o}}}\right)^2 u^2(E_{\mathrm{o}}) + \left(\frac{\partial E}{\partial E_{\mathrm{cal}}}\right)^2 u^2(\delta E_{\mathrm{cal}}) +$$

$$+ \sum_{i=1}^{n} \left(\frac{\partial E}{\partial \delta E_i}\right)^2 u^2(\delta E_i) = 6.1\ \% \qquad (7)$$

In the case of uniform PDF's the uncertainty contribution was determined as equal to the variation divided by √3 (estimate of standard deviation for this PDF). In the case of readout, the variation considered in the calculus was half-width of resolution, i.e., 0.5%.

The expanded uncertainty of the measurand, considering a confidence interval of 95% and assuming an output PDF of normal shape,

$$U_{95}(E) = 2.00 \cdot u(E) = 12\ \% \qquad (8)$$

which gives the estimate of the instrumental measurement uncertainty, related to a pointwise average measurement of illuminance.

IV. MEASUREMENT UNCERTAINTY OF *DF* USING THE EXPERIMENTAL METHODS

In the process of characterizing an indoor space regarding daylight factor, the methods establish a relation between each pair of illuminance measurement and the *DF* for a (*x*,*y*) position in a 2D surface.

In order to compare the performance of the methods accuracy, uncertainties related with the *DF* were calculated for methods 1, 2, and 3 (method 4 was not considered due to the approach being based in an indirect measurement of the illuminance thus requiring a deeper analysis of the effect due to intermediate model that relates luminance with illuminance).

The illuminance estimates and uncertainties were supported by experimental measurements obtained indoor and outdoor for the city of Lisbon (Portugal).

For E_{int}, two average values were taken, of 7 440 lux and 11 570 lux, to cover two different types of sky conditions. The uncertainty assumed in these cases was the instrumental standard uncertainty of 6.1% and was used for the three methods under comparison. Regarding the outdoor measurements, because of the experimental setup conditions, different average values measured being presented in Table 2.

Table 2. Experimental values used as estimates for the evaluation of DF with methods 1, 2 and 3

Case study	E_{int} / lux	E_{ext} / lux	E'_{ext} / lux	E_{Vext} / lux
Exp. 1	260	7 440	3700	2950
Exp. 2	580	11 570	5790	4580

The comparison also requires calculating the measurement uncertainties for each quantity, being different because the experimental setups are diverse. Therefore, in each case, the instrumental uncertainty needs to be combined (using GUM) with the other contributions related with the measured method and effects due to signal processing and operator (the two last, with no extra influence taken into account).

For method 1, as reference, the standard uncertainty considered was the instrumental uncertainty. For the methods 2 and 3, Table 3 presents the additional sources of error and the related variation and PDF adopted, in order to estimate its contributions for the uncertainty budget.

Table 3. Error sources variation and adopted PDF's related with the methods setup accounted for the evaluation of measurement uncertainty of the output quantity DF

Error source (method)	Method 1 Variation / %	Method 2 Variation / %	PDF
Orthogonality	---	5%	Uniform
Obstruction screen area	3%	0%	Uniform
Screen shading	1%	---	Uniform
Surrounding shading	---	2 %	Uniform
Distance of screen from the sensor	2%	---	Uniform
Screen reflectance	1%	1%	Uniform
Soil Reflectance	---	2%	Uniform

Considering this contributions, the standard measurement uncertainties obtained for the outdoor measurements are given in Table 4.

Table 4. Measurement standard uncertainties calculated for the internal and external measurements of illuminance related with 3 methods studied

$u(E_{\mathrm{int}})$ / lux	$u(E_{\mathrm{ext}})$ / lux	$u(E'_{\mathrm{ext}})$ / lux	$u(E_{\mathrm{Vext}})$ / lux
6.1	6.1	6.6	7.0

These values were considered as estimates of the input quantities in order to obtain the *DF* measurement uncertainties for the three methods. The evaluation of the measurement uncertainty of *DF* applied for methods 1, 2 and 3, followed the GUM approach [13] assuming no correlation between input quantities, being presented in equations (9) and (10) for method 1 (similar approach was made for methods 2 and 3).

$$u^2(DF) = 100^2 \left[\left(\frac{\partial DF}{\partial E_{\mathrm{int}}}\right)^2 u^2(E_{\mathrm{int}}) + \left(\frac{\partial DF}{\partial E_{\mathrm{ext}}}\right)^2 u^2(E_{\mathrm{ext}}) \right] \quad (9)$$

$$u(DF) = 100 \left[\left(\frac{1}{E_{\mathrm{ext}}}\right)^2 u^2(E_{\mathrm{int}}) + \left(-\frac{E_{\mathrm{int}}}{E_{\mathrm{ext}}^{\ 2}}\right)^2 u^2(E_{\mathrm{ext}}) \right]^{1/2} (10)$$

In order to validate the GUM approach, a Monte Carlo Method approach [15] was used, being the numerical evaluation developed using RStudio programming, with 10^6 runs for each calculation. The obtained results are shown in Table 5.

Table 5. Results of expanded uncertainty of DF, for 3 methods, obtained using GUM and MCM procedures

Case study		Method 1 $U_{95}(DF)$	Method 2 $U_{95}(DF)$	Method 3 $U_{95}(DF)$
Exp.1	GUM	0.60%	0.63%	0.65%
	MCM	0.60%	0.63%	0.65%
Exp.2	GUM	0.86%	0.90%	0.93%
	MCM	0.86%	0.89%	0.92%

The comparison of values obtained using GUM and MCM allows validating the use of GUM as appropriate for the calculus. However, small differences were found between the PDF's obtained using the two approaches, showing that output PDF's of *DF*, obtained using MCM, have some deviations from normal distribution. This could be confirmed by the evaluation of skewness, with values around of 0.26 (for the case study 1) and 0.32 (for the case study 2) and kurtosis, with values around 3.16 (for the case study 1) and 3.24 (for the case study 2).

The comparison of the PDF of the output quantity *DF*, for the case study 2 and using method 2, is illustrated in Figure 5, showing the difference between the normal curve (GUM) and the histogram obtained using MCM.

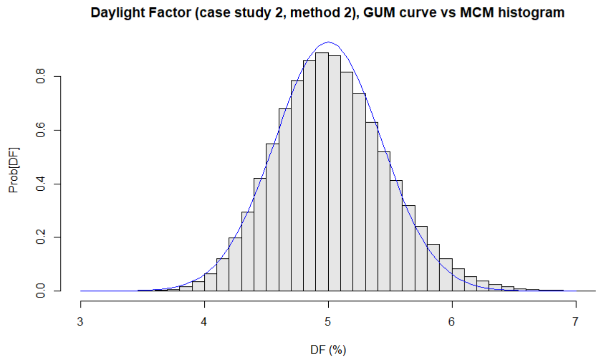

Figure 5. Comparison of PDF's for the quantity DF obtained using GUM and MCM for case study 2 and method 2.

V. CONCLUSIONS AND OUTLOOK

The measurement of the daylight factor in the context of the characterization of lighting in indoor of buildings is of great importance to environmental comfort and energy efficiency. This measurement can be obtained using different approaches based on similar input quantities but using alternative setups, thus requiring a study of the impact of these setups in the expected output results, usually, 2D distributions and profiles of daylight factor in these indoor spaces.

The evaluation of measurement uncertainties is a robust and efficient means of promoting the comparison of the performance of experimental methods, allowing to access information regarding the advantages and constrains of each approach and to establish conditions for simple good practice guidance to the application of requirements under conformity compliance.

In this paper four methods were presented but only three of them were compared, being the main reason the fact that method 4 uses a different measurement principle, using an indirect measurement approach in order to obtain the input quantity Illuminance by measuring the luminance with a defined theoretical condition. This implies that a different type of measurement instrument is used, requiring a specific analysis of the sources of error that contribute to the measurement uncertainty. In this case, the complexity of the measurement should account for the variability of the sky conditions and its influence in the measurement of luminance in order to develop a consistent comparison with the conditions needed for the measurement performed using methods 1, 2 and 3. The study of the impact of this component implies a dedicated study that is outside the scope of this paper, being under development by the authors, being intended to be published soon.

The results obtained are intermediate, being related with part of the stages of the complete measurement process, including the first two stages of measurement of illuminance and evaluation of the daylight factor, being the stages remaining of 2D distribution and profile of *DF* already under research. Considering the approach presented in this paper, some remarks can be stated, namely, that illuminance measurement uncertainty is high, reaching expanded uncertainty of 12% (although some bibliography mentions higher values of 15% to 25%, in our opinion its possible if good practice is not carefully considered), and it grows with alternative methods (as seen in Table 4), which was expectable considering that this alternative methods include in the setup conditions to obstruct lighting adding new experimental sources of uncertainty as they are not able to provide completely the conditions according with the theoretical relations of the mathematical models used.

Second conclusion is that the related daylight factors evaluated found with the three methods studied are nevertheless low, with values around 1%, considered appropriate for many of the intended use.

Finally, the comparison of the measurement uncertainty evaluation using GUM and MCM showed that there is some deviation from normality of the *DF* output quantity, which is common in ratio mathematical models, however, this deviation does not significantly affect the estimate of the quantity or the uncertainty interval.

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