‘Climate Connectivity’ in the Daylight Factor Basis of Building Standards

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Abstract

This paper describes a proposal for a daylight standard for CEN countries. It is now widely accepted in the research community, and increasingly so amongst practitioners, that the standards/guidelines for daylight in buildings are in need of upgrading. The essence of the proposal is that the 'target' for daylight provision should be founded on the availability of daylight as determined from climate files. The proposal is in fact a refinement of an approach originally described in a CIE document from 1970, and which appears to have been largely overlooked since then. The proposal states that a design should achieve a target daylight factor at workplane height across a specified percentage of the relevant floor area for half of the daylight hours in the year, where the target daylight factor is based on the provision of 300 lux. A key feature of the refinements are the formulation of the methodology such that the likelihood for misinterpretation and 'game-playing' is greatly reduced, if not eliminated altogether. The method, founded on cumulative diffuse illuminance curves, could be introduced relatively swiftly since it requires only modest enhancement of existing daylight prediction tools. In addition, the proposal will provide a sound 'footing' for eventual progression to evaluations founded on full-blown climate-based daylight modelling.

1 Background

By the late 1800s the pressure to accommodate an increasing number of people in the cities of the developing world led to taller and more tightly-packed building forms, thereby reducing and often eliminating entirely the direct view of sky from much of the useable, internal space. This in part led to the need for some objective measure of the daylighting performance of a space which could, if required, function as a tool to evaluate buildings at the planning stage. Daylight was at that time still the preferred source of illumination for both manual and clerical work – it was also 'free'. The work of Nordhaus has shown that the real cost of artificial light has dropped by nearly four orders of magnitude over the last two hundred years [1].

It is only over the last decade or two that we have come to appreciate once again the true importance of 'good' daylighting design for buildings. However the legacy of many years of effective downgrading of daylighting in the overall consideration of building design is still apparent today. Many standards for daylighting have hardly changed over 40 or more years, and often make no account of the actual availability of daylight. Attempts to progress matters have often resulted in less than satisfactory outcomes, e.g. vague or confusing criteria and/or methodologies. For example, the various 'clear sky options' recommended in both LEED and ASHRAE have resulted in approaches that are one or more of the following: confusing, inconsistent, prone to the vagaries of patterns in climate data, and/or without a proven rationale [2].

There is in effect an "impasse" that is hindering any progression towards standards that are founded on actual daylight availability [3]. It should also be pointed out that any attempt to create a standard based on objective criteria is going to be difficult, the complexity of the situation was made clear by Boyce [4] and the level set in any standard is going to be as much about what is economically possible as much as it is about what is technically necessary. A way around that impasse was proposed in the course of deliberations of the panel for CEN Technical Committee 169 / WG11 'Daylight'. This paper shows how the proposal could form the basis of a reliable and effective EU daylighting standard. It is possible for guidelines produced in one country to become *de facto* standards elsewhere if they are adopted locally. One example is the Building Research

Establishment Environmental Assessment Method (BREEAM) which has been taken up and promoted in a number of EU countries and beyond. The BREEAM recommendations for daylighting allow several approaches, some of which appear to accommodate a measure of local daylight availability using latitude as a proxy. This paper will make the case that the proposal made to CEN TC 169/WG11 offers a basis for an EU-wide standard that is more robust than BREEAM, has greater clarity, and is less prone to wilful or accidental 'game-playing'.

1.1 The daylight factor

The origins of the daylight factor (DF) are actually somewhat hazy since there does not appear to have been a seminal paper introducing the approach. The reference to its first suggestion in 1895 appears to be anecdotal and recalled a number of years later [5]. The daylight factor was conceived as a means of rating daylighting performance *independently* of the actually occurring, instantaneous sky conditions. Hence it was defined as the ratio of the internal horizontal illuminance E_{in} at some arbitrary point in a space to the unobstructed (external) horizontal illuminance E_{out} from a hemisphere of sky. Light from the sky can arrive at a point in a space directly if any sky is visible from that point, and also indirectly following one or more reflections from surfaces inside and outside of the space, Figure 1. The daylight factor is usually expressed as a percentage:

$$DF = \frac{E_{in}}{E_{out}} 100\% \tag{1}$$

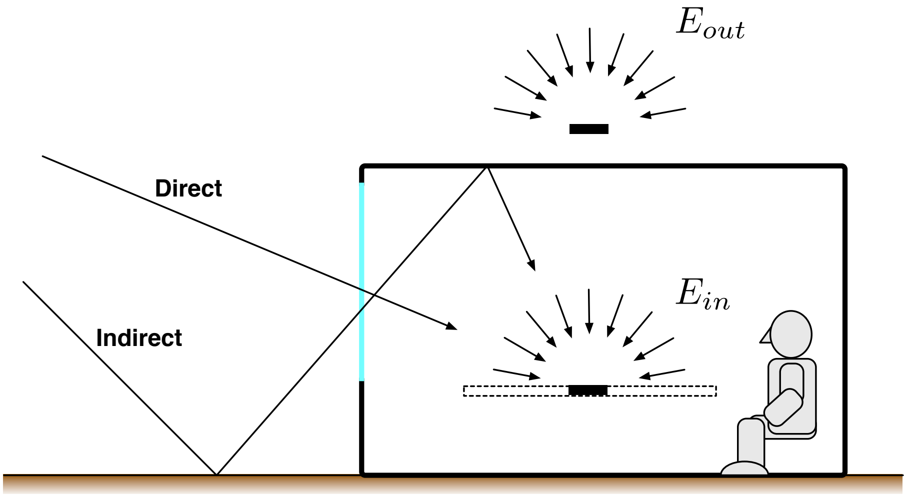

Figure 1: Definition of the daylight factor

However, the external conditions still need to be defined since the luminance distribution of the sky will influence the value of the ratio. At the time that the daylight factor was first proposed it was assumed that heavily overcast skies exhibited only moderate variation in brightness across the sky dome, and so they could be considered to be of constant (i.e. uniform) luminance. Measurements revealed however that a densely overcast sky exhibits a relative gradation from darker horizon to brighter zenith; this was recorded in 1901. With improved, more sensitive measuring apparatus, it was shown that the zenith luminance is often three times greater than the horizon luminance for some of the most heavily overcast skies [6]. A new formulation for the luminance pattern of overcast skies was presented by Moon and Spencer in 1942, and it was adopted as a standard by the CIE in 1955. Thus, since 1955, the daylight factor is strictly the ratio of internal illuminance to unobstructed (external) horizontal illuminance determined under a sky luminance distribution that conforms to (or is taken to be) the CIE standard overcast sky pattern:

$$L_\theta = \frac{L_z\,(1 + 2\sin\theta)}{3} \tag{2}$$

where L_θ is the luminance at an angle θ from the horizon and L_z is the zenith luminance. Notwithstanding the recent questionings regarding the validity of the CIE standard overcast pattern as the sole basis for the quantitative evaluation of daylight [2], it remains the most commonly used sky luminance pattern in guidelines and recommendations.

1.2 The average daylight factor

The average daylight factor (ADF) equation was first proposed by Lynes in 1979 [7]. In the original formulation the ADF calculated was that for all the enclosing surfaces of the space. The equation was revised by Crisp and Littlefair in 1984 following validation tests using scale models [8]. In the revised version the ADF calculated is that for the working plane only – it is usually expressed as follows:

$$\overline{DF} = \frac{TW\theta M}{A\,(1 - R^2)} \tag{3}$$

Where $\overline{DF}$ is the average daylight factor; T is the effective transmittance of the window(s); W is the net area of window(s); θ is the angle in degrees subtended in vertical plane by sky visible from the centre of a window; M is the maintenance factor; A is the total area of bounding surfaces of the interior; R is the area-weighted mean reflectance of interior bounding surfaces.

Consider the single and double aspect glazing arrangements for the 6 by 9 by 3.2 m space (W×D×H) shown in Figure 2. Using typical room reflectance values, the ADF calculated using the above equation is 4.9% – the same of course for both glazing arrangements. The ADF value predicted using (the rigorously validated) *Radiance* program is 5.2% for the single aspect space and 4.7% for the double aspect space. Notwithstanding the fact that the modified ADF equation was calibrated against measurements in scale models, where the inaccuracies are known to be considerably greater than the ±10% demonstrated for the *Radiance* program, the agreement is reasonably good. However, that is not the issue – what of the differences in daylight factor *distribution* for the two spaces? Whilst the spaces have the same ADF – as predicted by equation 3 – the distributions in daylight factor are markedly different.

This illustration also highlights the inadequacy of using an average value for the daylight factor – even when determined from a grid of points. Table 1 gives the average and median DF values for the two spaces shown in Figure 2. The simulated DF values in parentheses are those predicted with a 0.5 m perimeter gap between the sensor grid and the walls as recommended in LG5 [9]. The green rectangle superposed on the DF distributions in Figure 2 delineates the 0.5 m perimeter gap. For side-lit spaces the average is always greater than the median, especially so for single aspect glazing: 5.2% and 2.3% respectively. The average value is more open to game-playing than the median – note how the median is largely unchanged whether or not the LG5 guidance is followed. The median also is far more revealing about the luminous environment because it informs on the spatial distribution of the daylight factor: half the points will be above the median

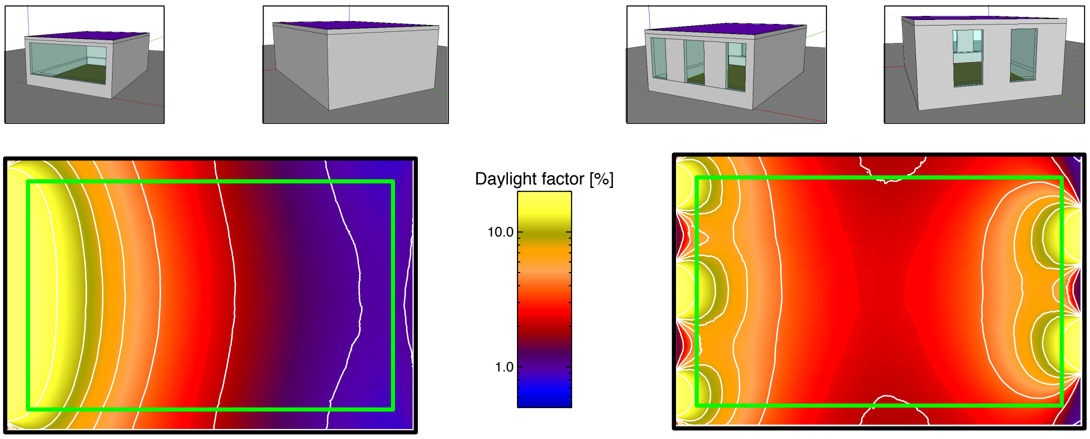

Figure 2: Daylight factor plots for single and double aspect spaces – same area glazing for both spaces

and half will be below. Notice that, not only is the difference between the single and dual aspect median values (2.3% vs. 3.3%) much greater than the difference in the ADF (5.2% vs. 4.7%), but the sense is reversed: the single aspect ADF is greater than the dual, but the dual aspect median DF is greater than that for the single aspect space (Table 1). Based on ADF alone, the single aspect space would be deemed to be *'better'* than the dual aspect. Notwithstanding its appealing ease and simplicity, the ADF cannot make any distinction between single and multi-aspect window designs (having the same glazing area for vertical windows). This would appear to be a fundamentally limiting feature of the ADF, greatly restricting its usefulness for design evaluation.

Glazing type	Calculated ADF	Simulated ADF (0.5m gap)	Simulated median DF (0.5m gap)
Single aspect	4.9%	5.2% (4.7%)	2.3% (2.3%)
Dual aspect	4.9%	4.7% (4.3%)	3.3% (3.4%)

Table 1: Calculated and predicted daylight factors

1.3 Absolute and relative values of illumination

In a 1937 paper P. J. Waldram claimed that: *"The eye is affected by ratio only, and is scarcely aware of huge variations in amount."* [10]. The evidence for this was based on an assessment of the daylight adequacy of 20 spaces carried on both a "bright day" and a "dull day" by a 'jury' of six members. Waldram's claim appears to have become the foundation for what is now an 'article of faith' amongst a number of practitioners, i.e. that there is no need to make any consideration of absolute values – the daylight factor ratio is all that is required. Waldram's assertion and the evidence in support of it were examined in a 1955 CIE paper by R. O. Phillips [11]. Phillips notes that:

> *If this investigation did, in fact, support the view that the daylight factor is more important than the actual illumination in determining the adequacy of the lighting, then the values of the daylight factor determined would be substantially the same on both types of day. If on the other hand, it is the illumination which is the more important, a higher value of the daylight factor would be required on a dull day that on a bright one.*

The original report of the 'jury' findings presented by Waldram included the curve shown in Figure 3. This was intended to *"summarise the results concisely and to deduce a figure of daylight factor which may fairly be said to represent the average opinion of the observers"* [11]. Phillips decomposes this curve into the data taken on the bright and dull days respectively. They clearly show different distributions, with a marked preference for a higher daylight factor value on a dull day compared to a bright one: the means were 0.20% (dull day) and 0.09% (bright day). Applying a paired t-test on the data, Phillips notes that: *"Since such a value could only arise by chance once in several millions of cases, the hypothesis that there is no difference must logically be rejected"*. In short, Phillips' analysis of the data makes the convincing case that, contrary to Waldram's assertion, the subjects were in fact expressing a preference for adequate absolute daylight levels rather than relative ones (i.e. daylight factors).

Phillips' paper is potentially of great significance since it offers a robust challenge to a rarely unquestioned assertion that has long been held as a fundamental tenet of daylighting design/evaluation. That is being so, a question presents itself: why has this paper been consigned to near-obscurity? This finding from the Phillip's paper is included here because Waldram's assertion has been so influential that it has framed much of the development of methodologies for the evaluation and testing of daylight performance in spaces. In particular for the proposal described here, whilst daylight factors are used, the target values for them are founded on the *availability* of absolute levels of daylight – which would appear to be in accord with what was actually determined by Waldram's 'jury'. It needs to be recalled that, at the time that Waldram's jury carried the assessments, notions of illumination adequacy were very different from what they are today, e.g. a few tens of lux back then compared to several hundred lux today. However, that consideration does not alter in the slightest the significance of Phillips' re-evaluation of the Waldram study. This and related studies by Waldram also serve as the basis for the "rights to light" schema devised for the determination of daylight injury. The methodology employed by Waldram was recently critiqued in a number of papers [12] [13] [14] [15].

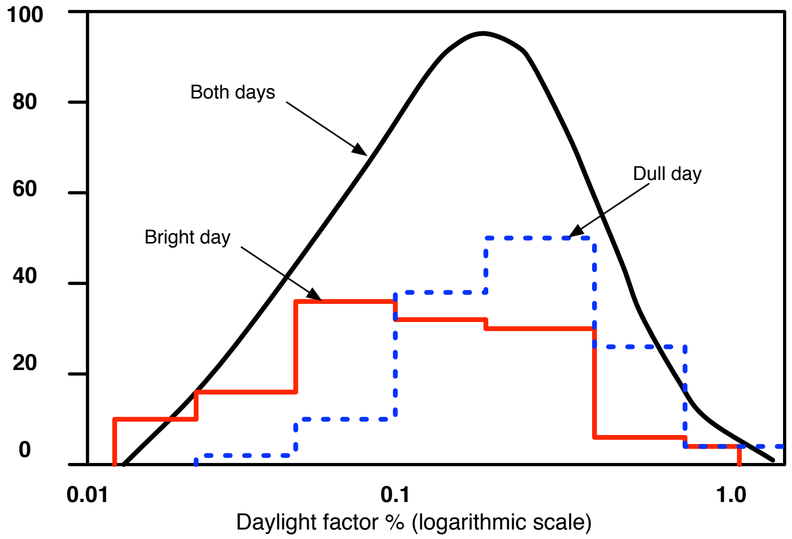

Figure 3: Distribution of preferred daylight factor values (after Phillips [11])

Recent studies have also shown either a preference for absolute rather than relative values, or a better correlation between user assessments of daylight adequacy and the simulated occurrence of absolute values rather than the (simulated) daylight factor. In the 2012 PIER report on daylight metrics, the 300 lux indicator value represented the best correlation to occupant preference for daylight sufficiency, based on 61 spaces in California, Washington and New York, comprising 484 occupant questionnaire responses and 324 expert questionnaire responses [16]. Similarly, for the Carpenter Center space evaluated by 60 architectural students, the contour for the (simulated) 300 lux daylight autonomy value had much better agreement with user assessments of daylight adequacy in the space than the (simulated) 2% daylight factor contour [17].

1.4 The marginalisation of the expert daylight designer

A half-century or more of often uncritical use of the DF has unfortunately led to a conflation in many minds of actual daylighting performance with what the daylight factor tells us. The DF is of course a proxy for daylight, but how good or bad a proxy depends on those important parameters that the DF approach cannot account for: prevailing climate (meaning the totality of sky and sun conditions) and building or facade orientation with respect the local site/context. The expert daylight designer does of course appreciate these intrinsic deficiencies. If sufficiently experienced, the designer can roughly 'guesstimate' the likely daylighting performance of the space and so recommend suitable facade treatments to temper the luminous environment. Thus the expert intuits what is called the spatio-temporal dynamics of natural illumination. One shouldn't be surprised to learn that the designer recommends different treatments for the north, south and east/west elevations. Nor that the advice would change if the building were relocated from, say, Stockholm to Madrid. After all, 'climate-adapted design' is a notion that relates closely to vernacular architecture. The designer may also carry out a daylight factor analysis because it is easy to do and the client can be charged for it – even if the designers take minimal notice of it themselves. If however the client demands that the daylight credit from a particular guideline document (e.g. BREEAM, LEED, etc.) must be achieved, then the success of the design will hinge to a large degree on the nature of the 'target' sought - invariably some measure based on the daylight factor. In which case, the best the expert designer can do is try to make good the failings that might, and often do, result from 'compliance chasing'. The client may even decide that the expert is not required since the facade treatment will be 'optimised' by someone using a lighting simulation tool: tweaking here and there until the some or other compliance target is reached. This has led one notable lighting expert to conclude that:

> *"...the only people who have a chance of getting it right are those who ignore everything the lighting profession proclaims through daylighting codes, standards and recommended practice documents."* [18]

Such sentiments are understandable. However, if the standards are proving to be insufficient to ensure a high likelihood that a good daylighting design is achieved, then researchers and practitioners should look to improving them rather than ignoring or ditching them altogether.

2 The Proposal Made to CEN TC169/WG11

The daylight in an interior space depends, firstly, on the availability of natural light (i.e. the prevailing climate at the site) and, thereafter, the properties of the space and its surroundings. Thus the evaluation of the provision of internal daylight should make account of the availability of daylight at the site in addition to accounting for the properties of the space [19]. It is proposed to change the basis of daylight evaluation in standards from relative values based on a single sky (i.e. the DF), to the annual occurrence of an absolute value for illuminance (i.e. lux) estimated from the cumulative availability of diffuse illuminance as determined from climate data, e.g. standardised climate files. This is an application of an established but now largely neglected approach [19]. This proposal offers several advantages. Firstly, since the estimate can be derived from daylight factors, it requires only a modest enhancement to existing software tools that predict DFs. Next, although not CBDM, the approach nevertheless provides some 'connectivity' to the prevailing climate.

The proposal is as follows. To demonstrate compliance with the standard, it is necessary to show that a target illuminance E_T is achieved across a percentage of the relevant floor area A_P for a percentage of the year Y_P. Internal illuminances are derived from annual data for diffuse horizontal illuminance appropriate to the location of the building/space under evaluation. In the following sections the rationale for selecting values for the parameters E_T, A_P and Y_P is described.

2.1 The target illuminance E_T

A number of studies have demonstrated that 300 lux of natural illumination is considered adequate by the majority of building users and also correlates with the notion of a "well daylit space" [17] [20]. In the 1970 CIE report 'Daylight', 300 lux is described as suitable illumination for *"prolonged office work"* [19]. See also the 2003 review of daylighting in schools by Wu and Ng where 300 lux of daylight is recommended in several guideline documents [21]. Additionally, design levels for artificial lighting are increasingly being set at or close to the 300 lux mark. Studies have revealed that the 'switch-on' probably for electric lighting is high for illuminances less than 100 lux and very low for illuminances 300 lux or greater [22]. Thus it is proposed that the target daylight illuminance should be 300 lux.

The target illuminance is derived from the cumulative availability of (unobstructed external) diffuse illuminance H as determined from standardised or similar climate files. The criterion to select and aggregate values from the annual diffuse illuminance time-series is described in a following section. For now, it is sufficient to simply note the relation between the target illuminance E_T, the target external diffuse horizontal illuminance H_T and the target daylight factor D_T:

$$\frac{E_T \times 100}{H_T} = D_T\% \tag{4}$$

This is of course just Equation 1 with different symbols. In other words, for a given external diffuse horizontal illuminance H_T, a daylight factor of $D_T\%$ is needed to produce an internal illuminance of E_T (i.e. of 300 lux).

2.2 The percentage of the relevant floor area A_P

The percentage of the relevant floor area should depend on the potential for the space to deliver daylight to the interior. The most typical is the multi-story side-lit space with windows on just one facade. For this type of space it is proposed that the target illuminance of 300 lux is achieved across 50% of the floor area (for the percentage of year Y_P). For multi-aspect glazing the value could of course be greater. Though care will be needed in the specification and indeed wording of any guidelines since it is possible to inadvertently discourage modest improvements in daylighting that fall short of the higher specification for, say, spaces with glazing on two facades. For example, say that the percentage of the relevant floor area for twin aspect daylighting was 75%. For spaces where only small additional windows are practicable on the second facade, it might not be possible to achieve the area target of 75%, and so the space would *not* meet the more onerous criterion. In which case, the designer might well decide to revert back to just having the main glazing on one facade. These unintended consequences are difficult if not impossible to avoid in any incremental rather than sliding-scale system of 'reward'.

Top-lit spaces are perhaps more straightforward in this regard, and the percentage area target should be fairly high because uniformly distributed apertures can be designed give even daylight distribution across the entire occupied floor area. The determination of practicable percentage area targets for other space/building types (e.g. 'borrowed light' from atria, non-uniformly distributed top-lit spaces etc.) could require more consideration.

2.3 The percentage of the year Y_P

There are a number of ways to select a percentage of the year for the evaluation of daylight provision. The selection criteria tested were of four types:

- A fixed period of the day, e.g. 'typical' working hours. For many latitudes this would include hours of darkness in winter.
- Based on sun position, i.e. as a proxy for daylight availability. The condition could be any arbitrary sun altitude $\geq 0°$.
- Based on diffuse horizontal illuminances that exceed a threshold, i.e. only those instances where a specified level of (external) daylight has been achieved.
- Based on a fixed proportion of the illuminance values in the climate dataset.

In order to make meaningful comparison between the different criteria, it was decided to compare the median value for the diffuse horizontal illuminance determined using each of the criteria. To further ease the comparison, the median diffuse horizontal illuminance was converted into a target daylight factor using Equation 4, where $E_T = 300$ lux i.e. the target illuminance value. In other words, whatever the selection period according to the various criteria, the daylight factor required to deliver 300 lux for half of that period was determined.

The outcomes for eight European locations covering a wide range in latitude and prevailing climate type were tested, Table 2. The climate files (freely available) were downloaded from the EnergyPlus website.[1] The last column in Table 2 gives the number of "sunny" days for each of the climate files. A sunny day was taken to be one where more than half of the daily total of global horizontal illuminance was due to direct solar radiation. This quantity varied from 49 days (Moscow) to 194 (Madrid).

The following conditions were tested: four fixed periods of the day; three sun altitude; three external diffuse horizontal; and, one fixed proportion of the total year. The results are give in Table 3. Taking the first group, it is evident that, as the period of the day included in the evaluation starts earlier and finishes later, the target daylight factor required to deliver 300 lux (for half of the evaluated period) increases. This, of course, is because a greater number of hours of darkness and low daylight availability are included in the assessment as the evaluated day length gets longer. Note also that the range in target daylight factor increases also. With increasing minimum sun altitude the sense of the previous trend is, of course, reversed. Similarly for increasing the minimum diffuse horizontal illuminance included in the evaluation. For the last case, it is advised to take

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[1] https://energyplus.net/weather

ID	City/ Station	Country	Latitude	Longitude	“Sunny” days
DEU-Hamburg	Hamburg	Germany	53.63	-10.00	50
ESP-Madrid	Madrid	Spain	40.38	3.68	194
FRA-Paris	Paris	France	48.87	-2.40	64
GBR-London	London	UK	51.50	0.18	71
ITA-Rome	Rome	Italy	41.90	-12.50	107
POL-Warsaw	Warsaw	Poland	52.23	-20.97	53
RUS-Moscow	Moscow	Russia	55.75	-37.63	49
SWE-Ostersund	Ostersund	Sweden	63.18	-14.50	59

Table 2: The eight climate files used in the sensitivity study

the highest 4,380 values of diffuse horizontal illuminance from the climate data (i.e. exactly half) and determine the D_T from the median of that sample.

To validate the sensitivity of extrapolating the highest values and using the median to determine D_T, the authors extrapolated all of the values between sunrise and sunset using the algorithm for astronomical daylength, or astronomical sunshine duration, defined as the period during which the solar altitude is greater than zero [23]. The median value of that sample varied insignificantly from extrapolating the 4,380 highest values; the general discrepancy of external diffuse horizontal illuminance between the two sample varied between 200 to 300 lux, which has no significant influence on D_T.

Criteria	Climate file ID / Target daylight factor D_T [%]								Rng
	DEU	ESP	FRA	GBR	ITA	POL	RUS	SWE	D_T%
09h $\leq$ h $\leq$ 16h	1.76	1.73	1.72	1.83	1.41	1.61	1.73	2.24	0.83
08h $\leq$ h $\leq$ 17h	2.03	1.84	1.92	2.04	1.57	1.81	1.99	2.52	0.95
08h $\leq$ h $\leq$ 19h	2.19	1.84	1.99	2.17	1.77	2.07	2.16	2.75	0.98
07h $\leq$ h $\leq$ 20h	2.70	2.09	2.33	2.66	2.12	2.56	2.70	3.32	1.23
Sun alt $\geq 0°$	2.17	1.78	1.95	2.19	1.78	2.09	2.11	2.58	0.80
Sun alt $\geq 1°$	2.10	1.75	1.90	2.14	1.75	2.04	2.01	2.47	0.72
Sun alt $\geq 5°$	1.91	1.67	1.75	2.01	1.65	1.83	1.83	2.02	0.37
$E_{dh} \geq$ 200 lux	2.09	1.76	1.89	2.13	1.73	2.00	2.03	2.49	0.76
$E_{dh} \geq$ 500 lux	2.04	1.75	1.85	2.09	1.69	1.95	1.98	2.41	0.72
$E_{dh} \geq$ 1,000 lux	1.97	1.72	1.80	2.05	1.67	1.90	1.92	2.32	0.65
Median 4,380 hgst.	2.16	1.77	1.94	2.17	1.77	2.07	2.09	2.55	0.78

Table 3: Sensitivity of 300 lux target daylight factor value to various criteria

Considering now the results as a whole, the following observations are made. The application of selection criteria based on a fixed period of the day applied uniformly across Europe may be less than ideal for a number of reasons. Firstly, periods of occupancy vary depending on building use and location. Also, intended use could change after the building is evaluated. Furthermore, selection of one period over another could favour (or disadvantage) some locations over others in terms of either achieving the specification and/or actual daylighting performance. For example, Spain uses Central European Time and so, given its longitude, solar time is markedly later than clock time for much of the country. This and other locale-specific factors (e.g. typical working period) suggest that a fixed period of the day is not a robust criterion for the purpose of evaluating the *intrinsic* daylighting performance of a space or building. Another potential issue with having a fixed period as the criterion is the quite distinct possibility that it may be applied incorrectly. For example, if the occupied period is defined as starting at 9 am and ending at 4 pm, it could erroneously appear in an assessment as an 8 hr rather than a 7 hr period. The authors have observed many instances where the users of, say, spreadsheets select *eight* rows with the timestamps: 09h, 10h, . . . 16h. Similar ambiguity exists in some building simulation software where it is not always clear how the tool interprets such seemingly unambiguous entries as "9" and "16" for "start" and "end" times: does that include the eighth hour (16h – 17h) or not? One would generally assume not. However, $09h \leq h \leq 16h$ could be taken as defining either a 7 hr or an 8 hr period depending how the $\leq$ condition is interpreted by user and/or the designer of the user-interface. The authors have observed errors resulting from this ambiguity at all levels: from postgraduate student projects to expert client reports.

As noted, the sun altitude condition serves as proxy for daylight hours. The condition sun altitude $\geq 0°$ will *generally* result in the selection of diffuse horizontal illuminance values greater than zero. But that will not always be the case, nor will the condition guarantee the selection of exactly half of the hours of the year (i.e. 4,380) as one might expect. This occurs because the continuous motion of the sun is considered only at fixed intervals (i.e. hourly) resulting in sampling 'boundary effects'. The diffuse horizontal illuminance condition serves a similar purpose as sun altitude, though the condition is now applied directly to the data to be sampled rather than via the proxy of sun altitude. Tests revealed that the condition $E_{dh} \geq 0\,\text{lux}$ was also prone to sampling 'boundary effects'. This could be because the protocols for preparing the various climate files from all the disparate sources was not identical, e.g. the criteria used to reset the negligibly small E_{dh} values to zero were different. Such effects have no bearing whatsoever on, say, a dynamic thermal simulation, but any procedure based on a proportion of the total (i.e. the median) will be sensitive to the distribution of the data. Thus consistency and robustness in the methodology are vital to avoid accidental blunders or deliberate game playing.

The authors propose therefore a method that reliably, and consistently, selects a fixed sample of diffuse horizontal illuminance values from the annual time-series. Thus avoiding any influence on the outcome resulting from 'boundary-effects' etc. The hours of daylight for evaluation are determined by rank-ordering (i.e. from highest to lowest) the 8,760 values for diffuse horizontal illuminance and then extracting the first (i.e. the highest) 4,380 hourly values. Note that the retained (i.e. highest) 4,380 values may include some zero values, or that the discarded 4,380 values may include some non-zero values. This is to be expected given the nature of illuminance data in climate files, and does not affect the outcome nor the validity of the process. The target daylight factors derived from the median of the selected E_{dh} values are shown in the last row of Table 3. Note that they are very similar, but not exactly the same as those for the sun altitude $\geq 0°$ condition. Because, as noted, that sun altitude condition cannot be relied upon to select exactly 4,380 E_{dh} values. The D_T values in the last row vary from 1.77% (for Madrid and Rome) to 2.55% for Ostersund – a range of 0.78%.

2.4 A minimum illumination recommendation

The Proposal includes a recommendation that a minimum illuminance of 100 lux should be exceeded across 100% of the space for half of the daylight hours. In practice, this is the same as recommending that the target minimum daylight factor value D_{TM} is not less than one third the target daylight factor D_T. Evaluations carried out on a number of typical side-lit office and classroom spaces indicated that, in the absence of internal obstructions, the minimum daylight factor is often not less than one third times the daylight factor in the middle of the space (see single aspect space in Figure 2). This suggests that, for many side-lit spaces, D_{TM} is likely to be achieved if D_T is achieved. Nonetheless, the minimum illuminance recommendation acts a safeguard against very poorly illuminated 'extremities' in daylit spaces.

3 An outline of the proposal

The following is the recommendation in the proposal for a single aspect side-lit space. An illuminance level of 300 lux should be exceeded over 50% of the space for more than half of the daylight hours in the year. Additionally, an illuminance level of 100 lux should be exceeded over 100% of the space for more than half of the daylight hours in the year. For spaces with rooflights, an illuminance level of 300 lux should be exceeded over 100% of the relevant area of the space for more than half of the daylight hours in the year. Thus, for spaces with rooflights, there is no need for a minimum illuminance requirement.

Whilst the recommendations are given in absolute values, it is expected that many practitioners will, in the first instance, use a daylight factor based evaluation. The proposal for single-aspect side-lit spaces can be described in terms of the daylight factor as follows:

> **A design should achieve a target daylight factor (D_T) at workplane height across half of the relevant floor area (A_{50}) for half of the daylight hours (Y_{25}) in the year, where D_T is based on the provision of a recommended lux value.**
> **The design should also achieve a target minimum daylight factor (D_{TM}) at workplane height across all of the relevant floor area (A_{100}) for half of the daylight hours (Y_{25}) in the year, where D_{TM} is based on the provision of a recommended minimum lux value.**

Definitions:

- The target daylight factor D_T and the target minimum daylight factor D_{TM} are derived from the median of the diffuse horizontal illuminance data for daylight hours by applying the daylight factor relation between internal and external diffuse illuminance.
- The daylight hours are defined as the 4,380 highest values for diffuse horizontal illuminance in the (rank ordered) data.
- The diffuse horizontal illuminance data used is appropriate to the locale of the building/space under evaluation.
- The relevant floor area A is the entire regularly occupied floor area for the space less a 0.5 m perimeter zone.

For the recommended illuminance of 300 lux, the corresponding daylight factor to be achieved is D_{300}. Similarly, for the recommended minimum illuminance of 100 lux the corresponding daylight factor to be achieved is D_{100}. Thus, to meet the recommendation for both:

$$D_T > D_{300} \quad \text{and} \quad D_{TM} > D_{100}$$

Target D_{300} and target minimum D_{100} daylight factor values for 33 EU and CEN capital cities and Moscow are given in the next section. Higher daylight levels than the recommended provision of 300 lux may be preferable depending on requirements. For this reason, two other levels are proposed; 'medium' daylighting and 'high' daylighting which refer to the provision of 500 lux and 750 lux respectively. The corresponding daylight factor values for these are also included in the table below.

3.1 Example target daylight factors for 33 capital cities

Target daylight factors for 33 EU and CEN capital cities and Moscow are shown in Table 4. the sources of diffuse horizontal illuminance data were the EnergyPlus website and, for cities not in the EnergyPlus database, the SATEL-LIGHT European Database of Daylight and Solar Radiation. In the first instance the authors would recommend the use of standardised climate files since the data are based on direct measurements. On the basis of limited testing for a handful of locations, largely good agreement in D_T (actually, diffuse horizontal illuminance values) between the standardised and satellite-derived data has been observed. Whilst this is encouraging, it would appear prudent to recommend some further testing of satellite-derived illuminance data against that from standardised climate files. Furthermore, the authors have noticed one or two standardised climate files that deliver median E_{dh} values a little different from what might be expected. Illuminances are sometimes derived from irradiance values using a luminous efficacy model. The authors recommend therefore that standardised climate files are also subject to some checking for consistency, etc. A report on quality assurance procedures for illuminance data from climate files is being prepared.

3.2 Distribution in the annual occurrence of diffuse illuminance values

The distribution in the occurrence of diffuse illuminance values above and below the median value for eight of the locales are shown in Figure 4 using the annual 'temporal map' format. The time-series data of 8,760 values for each locale have been rearranged into an array of 365 days (x-axis) by 24 hours (y-axis). Illuminance values lower than the median value for that locale are shaded black, zero values (i.e. night time) are shaded grey. Illuminances greater than the median value are shaded in false colour, the shades red through orange to yellow indicating progressively higher values (the magnitudes are not important for this illustration so no false-colour scale is given). A daylight saving time of 1 hour was applied to each of the locales (however it is noted that Russia recently ended the practice). The percentage of the 2,190 diffuse illuminance values above the median value falling between the hours of 09:00 and 18:00 are shown in each plot title. The amount varies from 80% for SWE-Ostersund to 98% for ITA-Roma.

As expected, the lower the latitude the higher the percentage of selected values that fall within the 09:00 – 18:00 period. Note that significant differences between local and solar time also play a part (e.g. ESP-Madrid). Even for SWE-Ostersund (latitude 63.18), 80% of the selected values fall within the notional 09:00 – 18:00 working period. The authors maintain that the advantages of the diffuse horizontal illuminance median approach outweigh the differences observed in the distribution of selected values shown in Figure 4.

3.3 Latitude dependency

The BREEAM guide recommends a step-wise latitude dependency in *average* daylight factor [24]. Here the latitude dependency in target daylight factor (D_T) for the 33 capital cities is compared with the BREEAM scheme. The comparison is plotted in Figure 5. Superficially, there would appear to be reasonable agreement in the general trend. How-

Country	Capital	Latitude [°]	Median E_{dh} [lux]	Target daylight factor values D_{100}	D_{300}	D_{500}	D_{750}
Cyprus	Nicosia	34.88	18,100	0.6	1.7	2.8	4.1
Malta	Valletta	35.54	16,500	0.6	1.8	3.0	4.5
Greece	Athens	37.90	19,400	0.5	1.5	2.6	3.9
Portugal	Lisbon	38.73	18,220	0.5	1.6	2.7	4.1
Turkey	Ankara	40.12	19,000	0.5	1.6	2.6	3.9
Spain	Madrid	40.45	16,900	0.6	1.8	3.0	4.4
Italy	Rome	41.80	19,200	0.5	1.6	2.6	3.9
FYR of Macedonia	Skopje	42.00	15,400	0.6	1.9	3.2	4.9
Bulgaria	Sofia	42.73	18,700	0.5	1.6	2.7	4.0
Romania	Bucharest	44.50	18,200	0.5	1.6	2.7	4.1
Croatia	Zagreb	45.48	17,000	0.6	1.8	2.9	4.4
Slovenia	Ljubljana	46.22	17,000	0.6	1.8	2.9	4.4
Switzerland	Bern	46.25	16,000	0.6	1.9	3.1	4.7
Hungary	Budapest	47.48	18,100	0.6	1.7	2.8	4.1
Austria	Wien	48.12	16,000	0.6	1.9	3.1	4.7
Slovakia	Bratislava	48.20	16,300	0.6	1.8	3.1	4.6
France	Paris	48.73	15,900	0.6	1.9	3.1	4.7
Luxembourg	Luxembourg	49.36	16,000	0.6	1.9	3.1	4.7
Czech Republic	Prague	50.10	14,900	0.7	2.0	3.4	5.0
Belgium	Brussels	50.90	15,000	0.7	2.0	3.3	5.0
United Kingdom	London	51.15	14,100	0.7	2.1	3.5	5.3
Poland	Warsaw	52.17	14,700	0.7	2.0	3.4	5.1
The Netherlands	Amsterdam	52.30	14,400	0.7	2.1	3.5	5.2
Germany	Berlin	52.47	13,900	0.7	2.2	3.6	5.4
Ireland	Dublin	53.43	14,900	0.7	2.0	3.4	5.0
Lithuania	Vilnius	54.88	15,300	0.7	2.0	3.3	4.9
Denmark	Copenhagen	55.63	14,200	0.7	2.1	3.5	5.3
Latvia	Riga	56.57	13,600	0.7	2.2	3.7	5.5
Estonia	Tallinn	59.25	13,600	0.7	2.2	3.7	5.5
Sweden	Stockholm	59.65	12,100	0.8	2.5	4.1	6.2
Norway	Oslo	59.90	12,400	0.8	2.4	4.0	6.0
Finland	Helsinki	60.32	13,500	0.7	2.2	3.7	5.6
Iceland	Reykjavik	64.13	11,500	0.9	2.6	4.3	6.5

Table 4: Median diffuse illuminance and ‘target’ daylight factor values for 33 capital cities

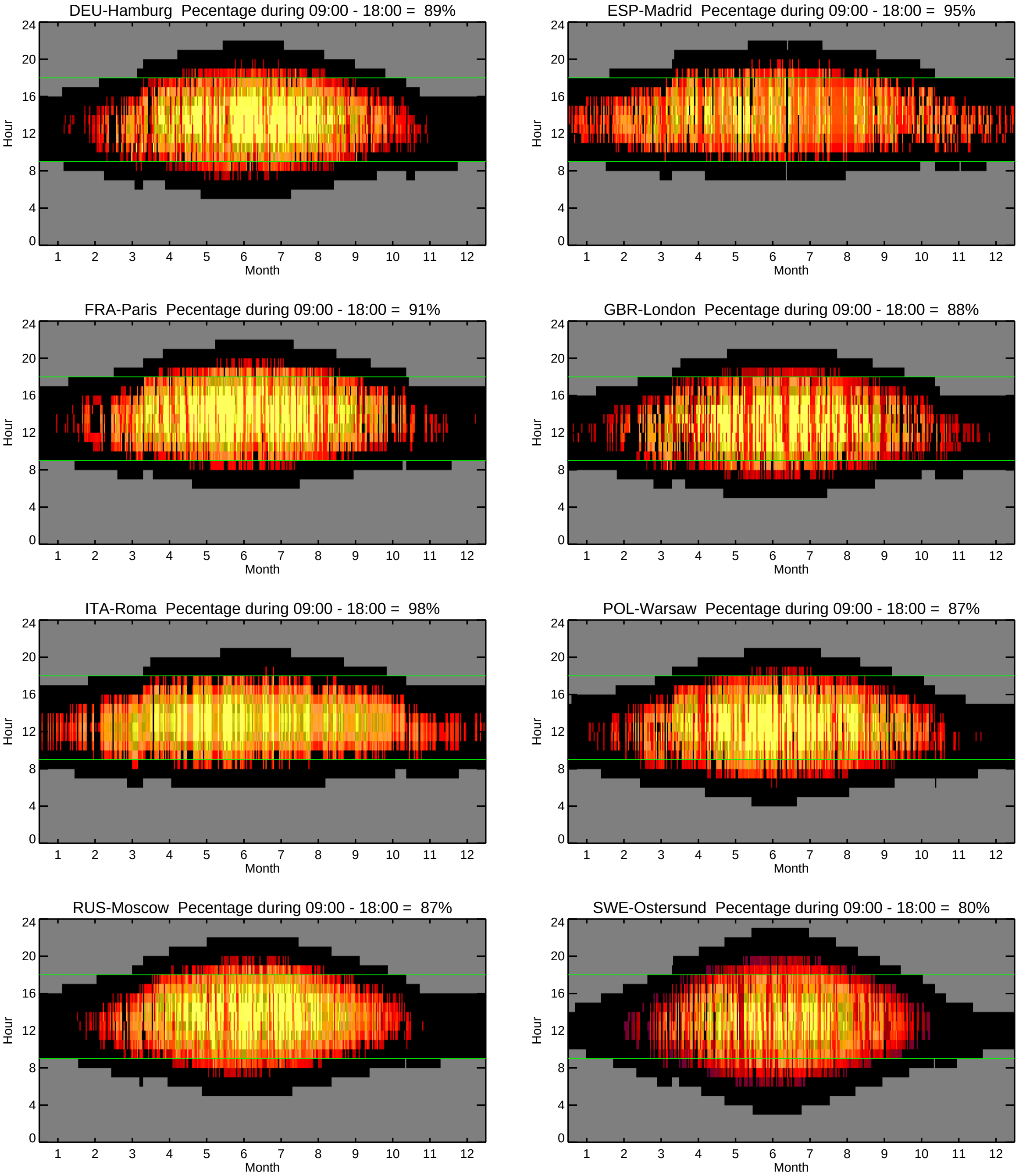

Figure 4: Distribution of selected diffuse data for eight locales (EPW climate files)

ever, the comparison is not like-for-like. As demonstrated in the example shown earlier (Figure 2 and Table 1), the average daylight factor can be markedly different from the median. Also, there is of course noticeable variation in D_T within each of the stepwise bands.

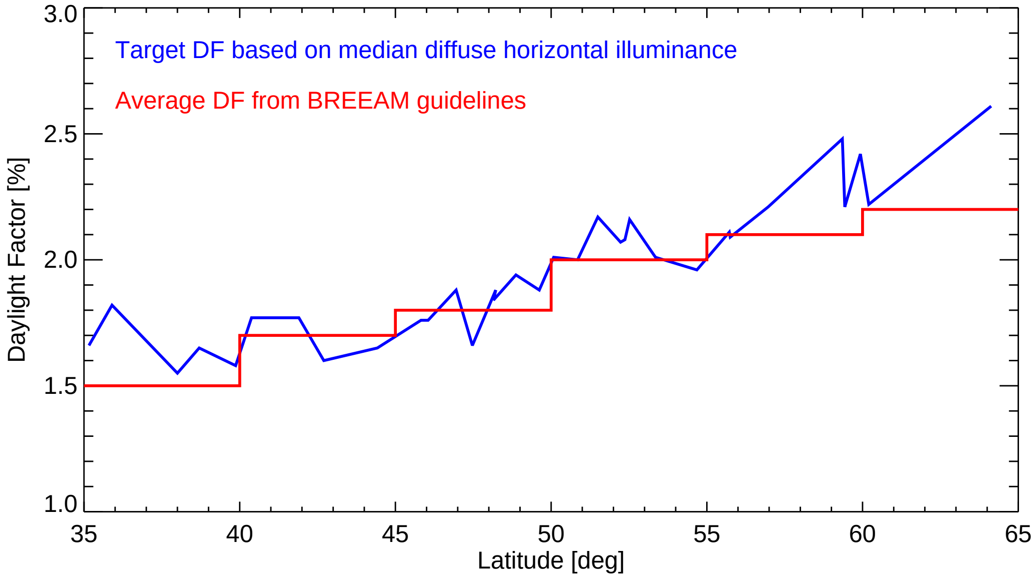

Figure 5: Comparison in latitude dependency

3.4 Validation of actual daylighting performance

Evaluation of an actual space against predicted daylight performance using the proposal described above is little different to that required for any ‘traditional’ daylight factor -based prediction. In principle, predicted daylight factors would be compared to measurements taken in the real space under suitable overcast sky conditions. In practice however this is rarely done because the practicalities of carrying out measurements under real sky conditions introduce many confounding factors, not least of which is the difficulty in determining if an actually occurring overcast sky conforms to the CIE standard overcast sky luminance pattern [25]. For these reasons, validation is usually carried out by indirect means [26]. The daylight factor in real spaces is more often inferred from some measurement of key geometrical parameters (accompanied by estimation of surface properties) rather than based on paired measurements of internal and external light levels [27]. In other words, the daylight factor is determined by *indirect* means. For this, the properties that need to be determined are:

1. Geometrical – to confirm that the dimensions and configuration of the building model assumed for the prediction stage are a sufficiently close match to the real building.
2. Surface properties – to confirm that the reflection/transmission properties assumed for the prediction were a faithful representation of those found in the finished building.

Both the geometrical and the surface properties of the real building can be compared against those employed for the prediction with rather more precision and reliability than relying solely on paired measurements of internal and external illuminance.

To minimise the risk of significant discrepancy between the modelled and actual space, any assumptions made at the prediction stage should be 'reasonable' according to normal, professional practice. Specified daylight design criteria need to consider building site characteristics, facade and roof characteristics, size and placement of window openings, glazing and shading systems, and geometry and reflectance of interior surfaces. All criteria should be verified by certain assumptions including degree of accuracy made. These assumptions should be declared reasonable and according to normal practice. As an example, the reflectance of the main surfaces needs to be considered carefully when assessing daylighting design of buildings, and often the recommended values of reflectances for the major interior surfaces would be in the following ranges: ceiling 0.7 to 0.9; interior walls 0.5 to 0.8; floor 0.2 to 0.4; exterior walls 0.2 to 0.4; with exterior ground usually set to 0.2. Deviations from these ranges are of course permitted, but justification should be given, e.g. a high reflectivity (0.6) exterior wall finish applied to a courtyard.

3.5 The CEN proposal and climate-based daylight modelling

Climate-based daylight modelling (CBDM) is the prediction of any luminous quantity (illuminance and/or luminance) using realistic sun and sky conditions derived from standardised climate data [28][29]. CBDM evaluations are usually carried out for a full year at a time-step of an hour or less in order to capture the daily and seasonal dynamics of natural daylight. Developed in the late 1990s, CBDM steadily gained traction – first in the research community, closely followed by some of the more forward-thinking practitioners. In 2013 the UK Education Funding Agency (EFA) made climate-based daylight modelling (CBDM) a mandatory requirement for the evaluation of designs submitted for the Priority Schools Building Programme (PSBP). School designs submitted to the PSBP must achieve certain 'target' criteria for the useful daylight illuminance metric. This is believed to be the first major upgrade to mandatory daylight requirements since the introduction of the daylight factor more than half a century ago. In the US, a climate-based daylight metric approved by the IESNA has appeared in the latest version of LEED. Perceived as long overdue in some quarters, in others the EFA decision was seen as controversial and is not without its critics [30]. Nevertheless, the EFA decision has resulted in CBDM becoming mainstream in the UK, and there is considerable enthusiasm for CBDM amongst designers/practitioners in the US.

The 'climate connectivity' which is the basis of the CEN proposal reaffirms the importance of absolute illuminance levels for the assessment of daylight provision. Phillips' re-evaluation of Waldram's data suggests that this reaffirmation is perhaps long overdue. In the medium term, adoption of the CEN proposal will also ease the transition to full-blown CBDM because designers and practitioners will have become more familiar with daylight illumination described in terms of absolute quantities (i.e. lux), their degree of occurrence throughout the year and the connection with the prevailing climate.

4 Summary

The proposal for a CEN daylighting standard described in this paper offers, the authors believe, a more robust basis for guidelines than any of the currently used schemes. The basis of the proposal is founded on the availability of daylight and the potential of the space to deliver absolute levels of illuminance over a specified period of the year. The methodology is both simple and clear with little potential for accidental or wilful 'game-playing' with regard to the outcome. The 300 lux target illuminance value is supported by a number of studies.

Perhaps the most important feature of the proposal is that it offers a significant advance over the most commonly used methods whilst requiring only a modest enhancement to existing practice. Practicality of implementation must, of course, be a major consideration for any CEN proposal of a new standard. At the time of writing, the proposal is due to proceed to a three month public enquiry sometime between July and October 2016.

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