

# Climate-Based Daylight Modelling And Its Discontents

John Mardaljevic PhD FSLL

School of Civil and Building Engineering, Loughborough University,  
Loughborough, Leicestershire, LE11 3TU, UK

[j.mardaljevic@lboro.ac.uk](mailto:j.mardaljevic@lboro.ac.uk)

## Abstract

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. Whilst it may appear that the case for CBDM has effectively been made, and that wider adoption in standards and guidelines is likely, it is important not to ignore or dismiss out-of-hand the critics of CBDM. Nor should it be overlooked that CBDM and the metrics derived using it are both still evolving. This paper: reviews the recent developments; the reactions to them; and, forecasts what might be expected in the near future. Attention is given to the formulation of the PSBP requirements for daylight and how the various stakeholders have responded to this major new development in building codes.

## 1 Introduction

### 1.1 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 [1][2]. 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. The widespread adoption of the *Radiance* lighting simulation system and, ultimately, CBDM was due in part to the outcomes from validation studies.

What is probably still considered the definitive validation study for any daylight prediction method (physical model, analytical or simulation) was carried out in the mid 1990s using data collected by the BRE as part of the International Daylight Measurement Programme – the data are sometimes referred to as the BRE-IDMP validation dataset [3][4]. That study showed that illuminances predicted using the *Radiance* system could be within  $\pm 10\%$  of measured values, i.e. within the accuracy limits of the measuring instruments themselves. This, quite remarkable, degree of precision needs to be judged alongside the high level of inaccuracies (often in excess of 100%) that were determined to be fairly typical for physical modelling [5]. The BRE-IDMP dataset was used to validate the daylight coefficient approach in *Radiance* which is the basis of many CBDM formulations. The author's daylight coefficient implementation was shown to have comparable high accuracy to the standard *Radiance* calculation [6]. CBDM has been applied to numerous real-world projects in a variety of ways to address 'traditional' and novel daylighting issues/problems.

## 1.2 The Priority Schools Building Programme daylight criteria

The PSBP daylight criteria were formulated by consulting engineers working in conjunction with the EFA. They decided to base the criteria on useful daylight illuminance (UDI). The useful daylight illuminance scheme is founded on occupant responses to daylight levels, as reported in several studies – see the original UDI papers for these [7][8]. First published in 2005, the UDI scheme had 100 and 2,000 lux as the lower and upper bounds for useful daylight illuminance achieved. The 2,000 lux value was revised upwards to 3,000 lux a few years later when data from more contemporary studies became available [9][10]. Setting the UDI range boundaries was, of course, a matter requiring some judgement since the various studies reported a scatter of values for a preferred upper limit. In comparison with more recent studies, the pre-2000 reports tended to suggest a lower tolerance to high ambient daylight illuminance levels. Also, the studies – then and now – were invariably carried out in office spaces. The visual display technology commonly used prior to the mid-90s (e.g. CRT screens) tended to be more prone to glare issues than that used today for three reasons: lower intrinsic brightness; less effective anti-reflective coatings; and, curved screens that could reflect light received from a wide angle. Modern screens are generally much more forgiving of higher ambient daylight levels. This could well explain why more recent studies generally report higher values than 2,000 lux as an upper limit which may prompt the lowering of blinds (in largely side-lit spaces).

The UDI achieved range of 100 to 3,000 lux can be further subdivided into two ranges called UDI-supplementary and UDI-autonomous. UDI-supplementary gives the occurrence of daylight illuminances in the range 100 to 300 lux. For these levels of illuminance, additional artificial lighting may be needed to supplement the daylight for common tasks such as reading. UDI-autonomous gives the occurrence of daylight illuminances in the range 300 to 3000 lux where additional artificial lighting will most likely not be needed. The UDI scheme is applied by determining at each calculation point the occurrence of daylight levels where:

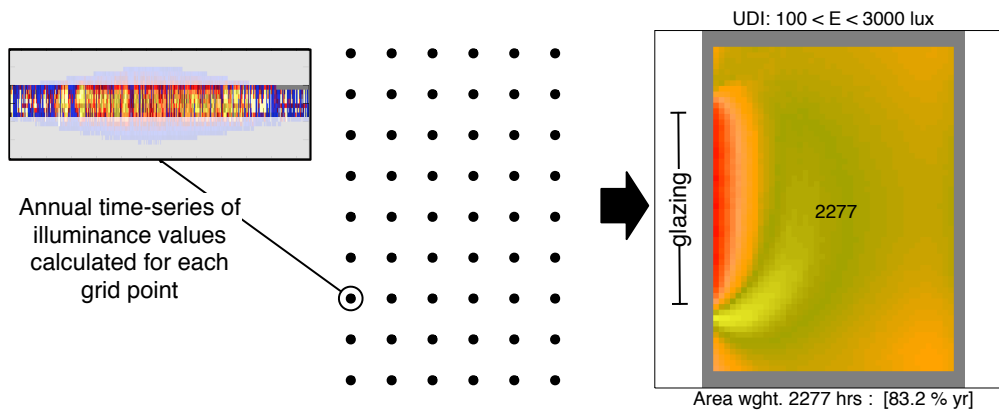
- The illuminance is less than 100 lux, i.e. UDI not achieved.
- The illuminance is greater than 100 lux and less than 300 lux, i.e. UDI supplementary.
- The illuminance is greater than 300 lux and less than 3,000 lux, i.e. UDI autonomous.
- The illuminance is greater than 3,000 lux, i.e. UDI exceeded.

Note that, for any sensor point, the daylight autonomy value for 300 lux is equal to the sum of the UDI autonomous and the UDI exceeded values. The 100 – 3,000 lux UDI achieved range is sometimes referred to as UDI combined.

The PSBP requirement specifies that the space-averaged value for the occurrence of illuminances in the range 100 to 3,000 lux during the period 08h30 to 16h00 is 80%.<sup>1</sup> It appears that the 80% criterion was based on a series of parametric tests carried out by the daylight specialists, evaluating a number of designs for different orientations. The space-averaged UDI value is determined by first predicting the annual time-series of daylight illuminance values at each ‘sensor’ point on a grid that covers the workplane, with a 0.5 m perimeter gap between the workplane and the walls. Then, for each grid point the occurrence of illuminance values within each of the UDI ranges is determined either as number of hours or as a percentage of the evaluation period, i.e. 08h30 to

<sup>1</sup>The original specification was for a range of 100 to 2,000 lux. Following correspondence with this author and others the range was adjusted to have the upper limit set to 3,000 lux.

16h00 for every day of the year, Figure 1. Lastly, the space average of the sensor grid values is determined.



**Figure 1: Schematic illustrating the computation of UDI**

### 1.3 Why did the EFA adopt CBDM?

The message regarding the importance of ‘good daylighting’ appeared to be getting across – but was it being implemented effectively? Statements such as this in design guidelines were fairly typical: “*maximising the use of daylight in order to improve student performance ... is an absolute imperative.*”<sup>2</sup> In a similar vein: “*An ADF [average daylight factor] of three percent is better than an ADF of two percent. Yes, it really is as simple as that.*” [11] Taking these recommendations at face value, it might appear that a botanical greenhouse would be the ideal classroom. A half-century or more of (occasionally uncritical) application of the daylight factor (DF) method had led to a ‘more is better’ mindset. And what of the impact of this on school designs? It has become something of an annual summer ritual to have the news media reporting on children fainting in new, overheating schools: “*The large amount of glass used is contributing to the problem of many classrooms becoming ‘unbearably hot’, officials said*” [12]. More generally, these BBC News reports note the concerns regarding glazing: “*... some new school designs which use a great deal of glass in their construction – with worries they can become overheated in summer*” [13]; “*... new buildings where much glass was used in the design*” [14]. Furthermore, attempts to incrementally advance the DF method using so-called ‘clear sky options’ (e.g. LEED, ASHRAE 189.1) were less than convincing [15]. This author was not a party to the EFA deliberations regarding the new requirement, however it does seem likely that some or all of the above would have figured in the decision to a greater or lesser degree.

## 2 Criticism of CBDM and the PSBP requirement

When the Education Funding Agency made CBDM evaluation a mandatory requirement, it evidently raised a number of eyebrows, and perhaps also hackles in equal measure. The reasons given for these reactions were many and varied. For some it was simply the ‘shock of the new’ – after a half-century of the daylight factor the sudden switch to CBDM was unexpected (as it was by this author also). Others perhaps felt that they might now be excluded from participating in consortia bids because they lacked in-house CBDM expertise. Another group seemed to be wary of what they considered to be an overly complex and unverifiable methodology. Furthermore, the useful

<sup>2</sup>Link to Scottish Government school design brief: [Optimising the Internal Environment](#)

daylight illuminance (UDI) metric specified by the EFA was considered by some to be unproven and, in particular, the compliance or ‘target’ values somewhat arbitrary. Many of these concerns are of course perfectly genuine. Voiced by experienced practitioners and daylight experts they cannot and should not be ignored. Two opinion pieces critical of these new developments appeared in late 2014 [11] [16]. The main part of this paper is an attempt to address – within the confines of a strict word limit – as many of these issues as possible in the sections that follow. The first considers the average daylight factor, which is favoured by both authors of the critical opinion pieces.

## 2.1 The average daylight factor

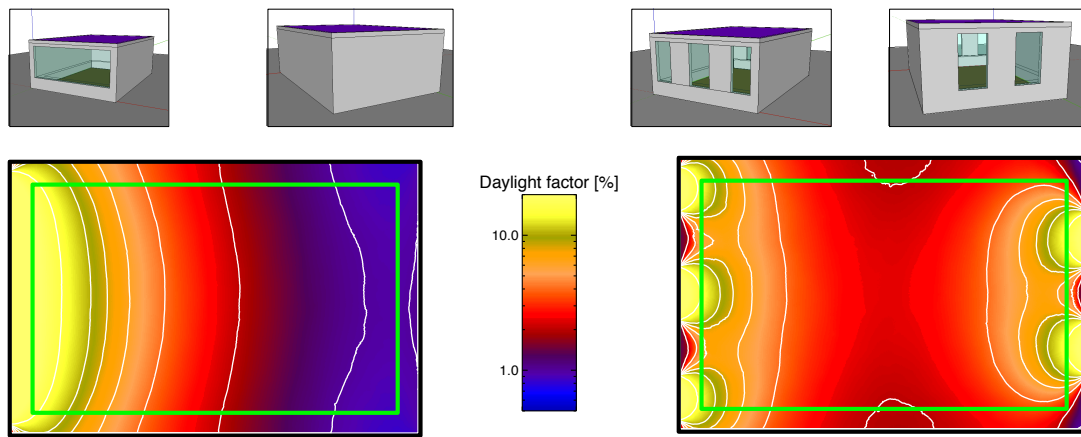
The average daylight factor (ADF) equation was first proposed by Lynes in 1979 [17]. In the original formulation the ADF calculated was that for all the enclosing surfaces of the space. The equation was revised by Crisp and Littlefair in 1984 following validation tests using scale models [18]. In the revised version the ADF calculated is that for the working plane only – it is usually expressed as follows:

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

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);  $\theta$  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 ( $W \times D \times H$ ) 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  $\pm 10\%$  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 1 – 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 [19]. 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. Arguably, 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 and half will be below. Notice how 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



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

than that for the single aspect space (Table 1). As Dr Jacobs notes, determination

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**

of the ADF is inexpensive in terms of both time and resources: ~1 minute and 1 napkin, respectively [11]. Thus, even the smallest of projects should allow for this in their budgeting. It is also an instructive thing to do at the very earliest stages of design. However, irrespective of any skepticism regarding the value of CBDM, this author finds it remarkable that some practitioners seem to prefer a single value ADF as an indicator of the ‘daylight performance’ of a space against a daylight factor distribution for the space. Notwithstanding its appealing ease, simplicity and the affordability of napkins, 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, whilst not hindering at all its application for ‘compliance chasing’ should the recommendation be simply to achieve an ADF of X%.

## 2.2 The US PIER report

The Lighting Journal article by Dr Jacobs cited the 2012 ‘Daylight Metrics’ PIER report from the US [20]. The PIER study failed to find any correlation with any preferred upper limit for daylight illuminance. Which might seem odd to anyone who has ever had recourse to draw blinds in order to moderate daylight/sunlight. Indeed, the report authors were also perplexed by this finding: *“In this sense, this negative finding should not be taken as conclusive, but deserves further investigation using other methodologies.”*

The PIER study attempted to find correlations between occupant assessments (including ‘snapshot’ evaluations of the space by visiting experts) and simulated metrics for the spaces. The simulations included the (simulated) operation of blinds where they were present in the actual building. Since these were all occupied spaces, any significant problems regarding direct sun exposure with the original provision of blinds had,



by and large, already been dealt with by the fitting of additional blinds (all of which were simulated). Hence it is perhaps not surprising the “negative finding” occurred. For this and other reasons, this author believes that a UDI evaluation of the fixed building form (i.e. no blinds/shades operation) is more revealing of the daylighting performance of a space than one where blinds/shades are simulated [21].

The PIER study was an ambitious and pioneering research project. Given the caution advised by the authors of the PIER report with regard to the finding noted above, to claim, as Dr Jacobs does, that the report “*tells us that it [UDI] simply doesn’t work*” [11] seems, at the very least, somewhat premature. Also, the PIER study included instances where many of the brightest spaces were top lit, with uniform illumination where sunlight was diffused via light wells or diffusing glazing. It may be that these space types present greater difficulties whatever the evaluation method. It may also indicate that UDI could be improved if  $>3,000$  lux illuminances due to direct sun were distinguished from those due to diffuse daylight (a refinement which is currently being investigated).

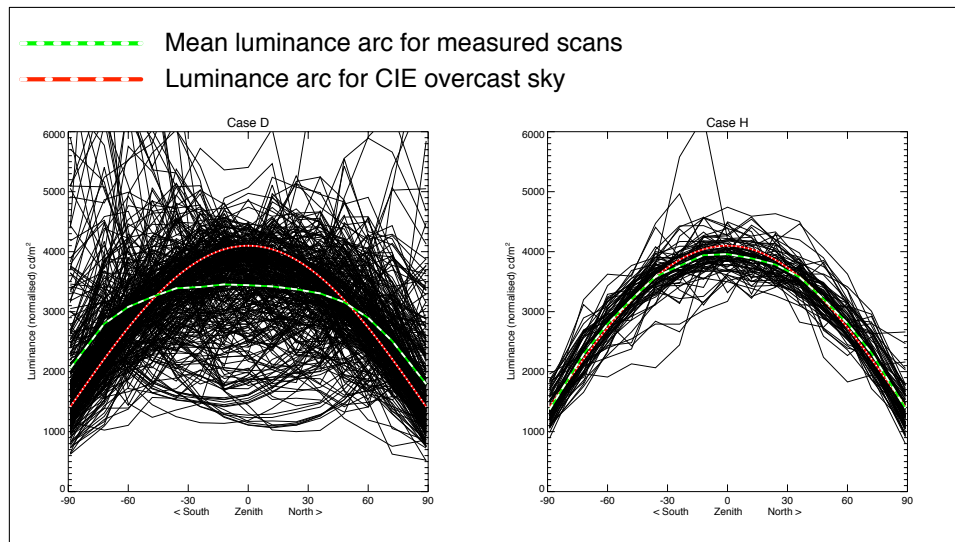
### 2.3 Daylight factors can be verified by measurement in the actual building

Another of the claimed advantages of the ADF is that daylight factor values derived from measurements taken in a real building can be compared with calculated/predicted daylight factors. However, as often appears to be the case, the “simple” things are never quite that straightforward when actually put into practice. To test a real building the actually occurring sky conditions need to at least approximate the luminance pattern of CIE standard sky. However, the CIE standard overcast sky is in fact – to quote Enarun and Littlefair – an “extreme” case of overcast sky [22]. Thus, skies that conform to the CIE standard overcast sky pattern are likely to be rarer than is generally imagined. Also, ensuring that an actual sky is even close to approximating the CIE standard overcast pattern is rather more difficult than many imagine. This was proven in a 2004 paper that examined the underlying assumptions often made in validation tests for daylight in real buildings [23].

Using the BRE-IDMP dataset, the assumption of CIE standard overcast sky conditions based on measurements of integrated quantities was tested for nine conditions, e.g. range limits for global horizontal illuminance and no-discernible direct sun indicated by a less than 1% between global and diffuse horizontal illuminance. For each of the skies conforming to the condition, the measured daylight factor (i.e. ratio of internal to external illuminance as a percentage) at each of the six photocells in the space was determined. The measured luminance arcs for one of those conditions (‘Case D’) are shown in Figure 3. In general, the actually occurring skies have a lower ratio between zenith and horizon than the  $3\times$  value in the definition of CIE standard. That results in a consistent over-estimation in the measured DF – leading to a greater likelihood in false ‘passes’. For example, at one of the photocell locations mid-way in the space, the measured DFs for the ‘Case D’ condition shown in the Figure 3 ranged from 0.6% to nearly 7%. The true value predicted under an exact CIE standard overcast sky was 1.12%. The only way to guarantee reliability in measurement of the DF is to ensure that – at the time of measurement inside the space – there is minimal variation between *four* (simultaneous) measurements of (unobstructed) vertical illuminance, ‘Case H’ in Figure 3. As is evident, for this stringent condition the actual skies do indeed approximate the CIE standard overcast pattern.

Another, potentially significant, confounding factor for any verification by measurement is the discrepancy between building model description and reality. Even before spaces

are occupied, it is likely that the actual reflectance properties of the space differ from that which may have been assumed and therefore modelled at the design stage. The smallest of surface articulations, e.g. pipes, conduits, textured ceiling tiles, etc., have the effect of lowering the effective reflectance of the surface through self-shadowing. Once occupied, posters, decorations, wall-hangings, book shelves etc. will all serve to modify the effective surface reflectance from the value originally conceived, and which may have been used in modelling to pass compliance criteria.



**Figure 3: Luminance arcs for measured sky scans**

Given all of these factors, and not forgetting the proven high accuracy demonstrated for the *Radiance* system, it would appear that verification of design intent is best carried out by simulation. An expert of proven ability should repeat the evaluation using a validated simulation program. The original calculations/predictions should be compared against these results. More generally, guidance based on real-world measurements should be given on the setting of appropriate reflectance values for calculation/simulation so that these better approximate the actual conditions in the finished/occupied building. The data to provide that guidance is presently lacking.

#### **2.4 CBDM: Too complex, too difficult, too unreliable?**

Daylight simulation in general and CBDM in particular have been described variously as “difficult”, “complex”, etc. Whilst there is certainly some truth in the belief that mastery of command-line *Radiance* is a hard-won skill, many practitioners make use of *Radiance* and other simulation tools when they are ‘bundled’ into easy-to-use packages. Since *Radiance* has been proven in validation tests to a greater degree than any other program, it is hardly surprising that it features as the lighting simulation ‘engine’ in a number of practitioner/end-user tools. Architecture students in some courses do hands-on CBDM using a *Radiance*-based simulation tool linked to a CAD package.<sup>3</sup>

All this shows that much of the complexity of the process can be hidden from the user, who can then concentrate on the simulation output. But what of the reliability of that output? Actual performance of the completed building can often differ markedly from what was simulated, and there is now much effort expended in “bridging the gap” between, say, predicted and actual energy consumption. Energy consumption of a building depends on numerous factors – not just the thermo-physical properties of the

<sup>3</sup>Link to: [2014 DIVA Day Student Competition winners](#)

building, but also the operational and behavioural characteristics. Although CBDM arrived two or more decades after dynamic thermal modelling became established, a reliable prediction of the daylighting performance of the *fixed* architectural form of the building should in fact be easier to achieve than a reliable prediction for, say, the energy consumption. For the simple reason that, unlike the thermo-physical response of a building, the (instantaneous) daylight conditions depend only on the state of the building (and the sun and sky conditions) at that moment – there is no illumination equivalent of thermal lag/inertia. Consequently, performance dependencies with (fixed building form) daylight are far less complex, with few in any ‘knock-on’ effects. Recently begun studies comparing UDI predictions using totally different CBDM formulations – and carried out by different users – have shown remarkable similarity in output thus far. These comparisons will be published in due course when completed. For basic daylight calculations, the Danish Building Research Institute’s evaluation of nine daylight simulation programs showed good agreement for the various packages using *Radiance*, and also for some other programs e.g. VELUX Daylight Visualizer [24].

## 2.5 Horizontal metrics and room appearance

The inadequacy of basing a lighting metric on measures restricted to a horizontal surface have been pointed out by a number of authors [25]. These arguments, based almost exclusively on artificial lighting scenarios, often describe how an emphasis on delivering so many lux onto the horizontal surface can result in inadequately lit spaces, e.g. rooms where the desk is sufficiently lit, but the overall appearance is that of a ‘gloomy cave’. These are, of course, all valid concerns for the electric lighting designer. But what of spaces illuminated by daylight? The parallels with electric lighting invoked by those critical of UDI, DA or any other horizontal-surface daylight metric, are, when examined, rather limited and perhaps even inapplicable. For the simple reason that inter-reflection *across* the space figures much more largely in light transport for daylight than it does for electric light. Since the majority of daylight spaces are totally or predominantly side-lit, reasonable levels of UDI on the horizontal simply could not be achieved without the key room surfaces – the walls and ceiling – having a ‘brightly lit’ appearance. Indeed, one would have to contrive a top-lit space where daylighting could result in low luminance walls and/or ceiling. Also, it should not be overlooked that the revised ADF method advocated by some of the CBDM critics was formulated to estimate the ADF across the *horizontal* workplane. Thus one would expect the ADF to be subject to the same scrutiny in this regard as UDI.

Nevertheless, the issue of CBDM evaluations of surface luminance is an interesting one. Perhaps one of the first simulation studies to evaluate the occurrence of surface luminance alongside the occurrence (and distribution) of daylight provision was that carried out for the New York Times project in 2005 [26]. The focus then was on visual comfort and the luminance of either the direct view through the windows or the brightness of the lowered fabric blinds. In addition to this author, I understand that others are looking to use CBDM to simulate annual profiles of surface luminance and to relate these to (horizontal) metrics such as UDI and DA. Prof. Tregenza’s timely reminder that ‘[daylight simulation] is a tool to be used creatively’ is unlikely to fall on deaf ears [16].

## 2.6 Too little daylight in the PSBP?

This is perhaps the most valid point raised by the critics, though in fact it is quite separate from the discussion regarding methodology, i.e. daylight factor versus CDBM. Is the 80% UDI 100 – 3,000 lux criterion too low? As noted, the figure was arrived at by daylight experts working with the EFA. In a number of cases, the guidance may



indeed result in smaller windows than was the case previously. Where before solar gain was a significant factor in overheating, less glazing may be no bad thing – when blinds/shades are down (and lights are on) there is no ‘daylight benefit’. Keeping within the UDI framework, the daylight provision could be increased by applying one or more of the following adjustments: increasing the target value of 80%; using instead the UDI-autonomous range 300 – 3,000 lux; or, increasing the upper limit to 4,000 lux or higher. Is there a compelling case to adjust the criteria to result in greater daylight provision? That remains a moot point. This author’s preference would generally be for more rather than less (useful) daylight. Providing, of course, that other performance criteria were not unduly impacted upon. Until there is a greater abundance of reliable daylight *performance* data for buildings under normal use, the setting of targets will inevitably involve a degree of judgement.

## 2.7 Miscellaneous reactions

Some of the reactions to the emergence of CBDM have been perplexing. As if some of the terms used for daylight evaluation weren’t confounded enough already (e.g. the various ‘clear sky options’ in LEED & ASHRAE), the suggestion that the application of orientation factors is somehow “*climate-based*” hardly brings clarity to the situation [11]. Firstly, it’s probably fair to note that very few practitioners make use of the orientation factors. Secondly, it’s not entirely clear just what, in practice, is the consequence of the orientation factor. A directional bias (across the compass points) in diffuse illuminance can only arise due to the presence of the circumsolar disc, which in turn indicates the presence of direct sun. In an actual building, direct sun entering a space may lead to the lowering of blinds – which is likely to reduce rather than increase the daylight entering the space. So, might the ‘orientation effect’ in reality be more a case of ‘blinds down, lights on’ rather than a 1.55× uplift in daylight provision? It hardly needs pointing out that, in a CBDM evaluation, instantaneous illuminance values under sunny sky conditions can be of the order of tens of thousands of lux for a space with south facing glazing, and just a few hundred for north facing glazing. Thus ratios of 50× or more are typical. The north-south ratio for the British Standard (BS8206-2) orientation factors is about 1.6×. Of course, none of this may in fact matter (see previous note re: how infrequently the method is actually used).

Even more perplexing has been the impression that the emergence of CBDM somehow signifies the end of a ‘golden age’ of daylighting evaluation and design. From this author’s perspective, a Panglossian acceptance of the status quo – as it was – seems unwarranted by the evidence. And especially so for school buildings where the 2008 report by CIBE made the national press: “*Government body criticises 80% of new [school] building designs*” [27]. Lastly, and perhaps most perplexing of all, was the (alarming) invocation of the disease “rickets” in the context of an article criticising the PSBP daylight requirement [11]. Since Dr Jacobs must surely know that vitamin D synthesis indoors behind glass is negligible, and that outdoor exposure to direct sun is required [28], one must assume that this was done merely for ‘dramatic effect’ rather than to enlighten the debate.

To summarise all of the above: much of what has been portrayed as ‘simple’ and ‘reliable’ is, on inspection, never quite that straightforward when put into practice. Conversely, some of the seemingly ‘difficult/complex’ evaluations (i.e. CBDM/UDI) are, in fact, not quite as difficult, complex or unreliable as perhaps first imagined.

### 3 Postscript

The final part of this paper briefly discusses some of the ways in which the introduction of CBDM is having an impact on daylighting practitioners, designers and building contractors.

#### 3.1 It's 'good to talk'

The appearance of the 'clear sky options' in guideline documents suggested several trends, none of them very encouraging. Firstly, there appears to be a 'disconnect' between what is known at the grassroots (e.g. by researchers and practitioners) and what can happen on expert panels. Is it possible that daylighting, and daylight experts, had become so marginalised – at many levels – that they fail to gain due consideration when panels are convened? In other words, it's perceived as acceptable for non-experts to 'fill-in' when it comes to daylighting. Articles that claim (emphatically in some cases) that a daylight evaluation "*really is as simple as*" carrying out an average daylight factor calculation may serve only to reinforce any such prejudicial notions. Another worrying indication is what appeared to be a lack of critical engagement within the daylighting community – much of what had appeared in print over the years was accepted without question. For example, see Chynoweth's 'forensic' examination of the basis for the "grumble point" in the rights to light methodology [29]. Whilst this author believes that much (but not all) of the criticism levelled against CBDM is misplaced, and, one hopes, adequately addressed in this paper, the fact that vigorous discussion is now taking place is to be welcomed by all in the daylighting community.

#### 3.2 CBDM in the PSBP: A good idea but hardly at the best time?

Cost-cutting across all the school building programmes has been severe. The funding allowance for 'Baseline Designs' is approximately £1,500 per square metre. Inevitably this has resulted in the adoption of standardised or 'template' designs, whereby replication of the same features – including facade detailing – across, say, all classrooms can help to keep costs down. If a CBDM evaluation reveals one thing it is that daylight performance has a significant dependency on window orientation. If standardised designs are to be used, it is hoped that contractors could make available two or three different classroom facade/glazing configurations without incurring an undue cost overhead. Perhaps the CBDM evaluations will help to refocus some of the emphasis onto basic daylighting design parameters, thereby strengthening the case for appropriate cost allocations – some of this may already be happening (see following section).

#### 3.3 Unanticipated outcomes

Following informal discussions with a number of practitioners who have worked on EFA schools, it is possible to discern a few unanticipated and largely positive outcomes that may prove to have far-reaching consequences. Prominent in these discussions was mention of the client's "engagement" with the daylight design and evaluation process. Clients, it seems, understood the UDI outputs with little difficulty, and began to consider the importance of massing and orientation. These were often people who were familiar with the daylight factor, but for whom the traditional method was an abstraction, and so all too easy to ignore. The daylight factor is "simple" until one starts to wonder: "what does an average DF of X% *really* mean in terms of the actual illumination of a space?" CBDM and UDI have been used, this author has learnt, to good effect on non-EFA schools also. Perhaps occasionally to better effect since the cost constraints are often not so severe. This author has heard of several instances where UDI evaluations of schools have been used to make the case for effective multi-aspect daylighting design.

Ideally, this and related anecdotal evidence on how the industry is responding to the introduction of CBDM needs to be compiled and documented – an ongoing Loughborough PhD research project on daylighting design for schools will be collecting some of this data.

As might have been expected, concerns were raised regarding the preparedness of the industry to respond to the new requirements. In particular, what provision was there for offering training in CBDM? Initially, it appears that the EFA decision was based in part on an assessment of existing capacity, which was deemed to be sufficient. Nevertheless, the new requirement has created something of a groundswell of more general interest in CBDM amongst practitioners, i.e. not just those working on PSBP submissions. Some training courses are available (e.g. occasional DIVA4Rhino workshops), though it is probably the case that most current and emerging CBDM practitioners are largely self-taught. CBDM principles are taught at masters level on the Loughborough 'Low Carbon Building and Design Modelling' MSc, though suitable material would also be appropriate for architecture undergraduate students. Education at various levels regarding daylighting in general and CBDM in particular is an area where development is needed.

CBDM appears to be the 'spark' that has ignited a long-overdue debate regarding the practice of daylight evaluation and the formulation of daylight standards. Long may it continue – and, it is hoped, continue to produce more *light* than heat!

### Funding

No grant or commercial funding was received for the work reported in this article.

### Acknowledgements

The author is indebted to Eleonora Brembilla and Nafsika Drosou (both Loughborough University) for insightful discussions during the conception of this paper and comments on the first draft. Prof. Mardaljevic acknowledges the support of Loughborough University. The suggestions from two anonymous referees are gratefully acknowledged.

### References

- [1] J. Mardaljevic. Simulation of annual daylighting profiles for internal illuminance. *Lighting Research and Technology*, 32(3):111–118, 1 2000.
- [2] C. F. Reinhart and S. Herkel. The simulation of annual daylight illuminance distributions – a state-of-the-art comparison of six RADIANCE-based methods. *Energy and Buildings*, 32(2):167–187, 2000.
- [3] J. Mardaljevic. Validation of a lighting simulation program under real sky conditions. *Lighting Research and Technology*, 27(4):181–188, 12 1995.
- [4] J. Mardaljevic. The BRE-IDMP dataset: a new benchmark for the validation of illuminance prediction techniques. *Lighting Research and Technology*, 33(2):117–134, 2001.
- [5] S. W. A. Cannon-Brookes. Simple scale models for daylighting design: Analysis of sources of error in illuminance prediction. *Lighting Research and Technology*, 29(3):135–142, 9 1997.
- [6] J. Mardaljevic. *Daylight Simulation: Validation, Sky Models and Daylight Coefficients*. PhD thesis, De Montfort University, Leicester, UK, 2000.
- [7] A Nabil and J. Mardaljevic. Useful daylight illuminance: a new paradigm for assessing daylight in buildings. *Lighting Research and Technology*, 37(1):41–57, 2005.
- [8] A. Nabil and J. Mardaljevic. Useful daylight illuminances: A replacement for daylight factors. *Energy and Buildings*, 38(7):905–913, 2006.

- [9] David Lindelöf and Nicolas Morel. Bayesian estimation of visual discomfort. *Building Research & Information*, 36(1):83–96, 2008.
- [10] J. Wienold. *Daylight Glare in Offices*. PhD thesis, Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany, 2009.
- [11] A. Jacobs. Getting the measure of daylight. *The Lighting Journal*, pages 15–17, September 2014.
- [12] L. Clark. Pupils pass out in £25million PFI schools as new classrooms overheat. *The Daily Mail*, 18th July 2009.
- [13] S. Coughlan. Heat limit demand for classrooms. *BBC News*, 3rd April 2010.
- [14] S. Coughlan. Overheated schools stop pupils learning, say teachers. *BBC News*, 8th April 2012.
- [15] J. Mardaljevic and J. Christoffersen. A Roadmap for Upgrading National/EU Standards for Daylight in Buildings. *CIE Midterm conference – Towards a new century of Light*, Paris, France 12-19 April, 2013.
- [16] Peter Tregenza. Opinion: Climate-based daylight modelling or daylight factor? *Lighting Research and Technology*, 46(6):618–618, 12 2014.
- [17] J. A. Lynes. A sequence for daylighting design. *Lighting Research and Technology*, 11(2):102–106, 06 1979.
- [18] V. H. C. Crisp and P. J. Littlefair. Average daylight factor prediction. *Proc. Nat. Lighting Conf., Cambridge (London: CIBSE)*, 1984.
- [19] LG5 CIBSE/SLL. *Lighting Guide 5: Lighting for Education*. Chartered Institution of Building Services Engineers, London, 2011.
- [20] Heschong Mahone Group. Daylight Metrics - PIER Daylighting Plus Research Program. *Final Report to the California Energy Commission, CA, USA*, 2012.
- [21] J. Mardaljevic. Daylight Performance Criteria. *Energy Forum – Advanced Building Skins*, Bressanone, Italy, 5–6 November, 2013.
- [22] D. Enarun and P. Littlefair. Luminance models for overcast skies: Assessment using measured data. *Lighting Research and Technology*, 27(1):53–58, 1995.
- [23] J. Mardaljevic. Verification of program accuracy for illuminance modelling: Assumptions, methodology and an examination of conflicting findings. *Lighting Research and Technology*, 36(3):217–239, 2004.
- [24] A. Iversen, N. Roy, M. Hvass, M. Jorgensen, J. Christoffersen, W. K. E. Osterhaus, and K. Johnsen. Daylight calculations in practice: An investigation of the ability of nine daylight simulation programs to calculate the daylight factor in five typical rooms. *Danish Building Research Institute, SBI*:26, 2013.
- [25] C. Cuttle. Towards the third stage of the lighting profession. *Lighting Research and Technology*, 42(1):73–93, 3 2010.
- [26] E. S. Lee, S. E. Selkowitz, G. D. Hughes, R. D. Clear, G. Ward, J. Mardaljevic, J. Lai, M. N. Inanici, and V. Inkarojrit. Daylighting the New York Times headquarters building. *Lawrence Berkeley National Laboratory. Final report LBNL-57602*, 2005.
- [27] R Booth. £35bn revamp will produce generation of mediocre schools. *Guardian Newspaper*, 21 July 2008.
- [28] RCPC. Rickets soars as children stay indoors. *Royal College of Pediatrics and Child Health*, 22 January 2014.
- [29] Paul Chynoweth. Progressing the rights to light debate: Part 3: judicial attitudes to current practice. *Structural Survey*, 27(1):7–19, 2009.