Real-World Validation of Climate-Based Daylight Metrics: Mission Impossible?

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Abstract
One of the criticisms of metrics founded on climate-based daylight modelling (CBDM) is that they are unverifiable in practice. This criticism received some attention following the decision in 2013 by the Education Funding Agency to make CBDM and the useful daylight illuminance (UDI) metric a mandatory requirement for the evaluation of designs submitted for the Priority Schools Building Programme. Some of the difficulties related to the validation of CBDM metrics apply also to daylight factors. However, several other challenges need to be addressed and practical solutions found before any attempt at validation of CBDM metrics can be made. This paper identifies those challenges and describes a framework for the practical evaluation of daylighting performance in real world settings, and thus a basis for the validation of CBDM metrics. The task of validation requires a conflation of state-of-the-art techniques in measurement and modelling. Measurement techniques under consideration include high dynamic range imaging and 'smart sensors'. A key obstacle to real world validation in, say, classrooms is that it is often not possible to rely on measurements of illuminance taken on the horizontal plane because such locations are rarely free from disturbance during normal use. It becomes necessary therefore to measure illuminance at more reliable locations (e.g. walls) and use these as a proxy for illuminance performance on the horizontal. The relation between wall and desk performance is space-specific and can be determined using CBDM. The first steps towards practical application of this framework are described.
Keywords Daylight, simulation, validation, compliance.

1 Background

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. Mardaljevic's daylight coefficient implementation (latterly referred to as the 4 component method) 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 the useful daylight illuminance (UDI) metric. The useful daylight illuminance approach 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%.[1] It

[1] The original specification was for a range of 100 to 2,000 lux. Following correspondence with Mardaljevic and others the range was adjusted to have the upper limit set to 3,000 lux.

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

2 Validation and building performance

Validation of predicted building performance against actual measurements in the real building under normal occupation is relatively straightforward in principle, but can be rather difficult in practice depending on which performance parameter(s) are under evaluation. For overall energy consumption, it is a simple matter to compare meter readings with predicted values. Divergence between measured and predicted values can be large, and there may be many reasons for this [11]. Whilst significant differences between actual and simulated prevailing meteorological conditions can occur, the causes for large divergences between predicted and actual energy consumption often result from other, operational factors, e.g. commissioning of building energy management systems (BEMS), unexpected user overrides of heating/ventilation systems, etc. A key comfort parameter is the ambient air temperature. As a matter of course for most modern buildings with a building energy management system, the ambient air temperature will be monitored automatically in most if not all of the occupied spaces. Additionally, carbon dioxide levels may also be monitored as input data for the ventilation system. Historical monitored data from a BEMS can often be accessed remotely, e.g. through a web-based interface[2]. So, for anyone wishing to carry out an evaluation of, say, long-term ambient air temperatures in spaces, the data may already have been collected.

For a large building it is fairly common for the BEMS to record several hundred channels of data at 15 min intervals. However, for a majority of typical non-residential occupied buildings (e.g. offices and schools), not a single measurement of absolute light levels (i.e. illuminance) is taken. These buildings do not contain any device to record light levels in any of the occupied spaces. Only for specialist applications is the monitoring of illumination levels integrated into the BEMS, e.g. the daylight system in the National Gallery, London, UK. Note, there may be various light sensors in offices/classrooms to, say, control artificial lighting levels in response to daylight availability. However, these devices are generally designed to sense some arbitrary measure of ambient light levels, and, in the main, they do not have the physical characteristics to measure illuminance as it is strictly defined. Furthermore, it is unlikely that one could determine any form of reliable relation between a sensed 'light level' and actual illuminance in lux. Thus, in contrast to temperature, there are no readily available repositories of data on illuminance levels in generally occupied spaces that could be used for validation purposes. This situation highlights the unfortunate fact that the market demand for devices to measure *and* record/log illuminance levels in typical building spaces is almost zero[3]. Consequently, the long-term monitoring of illuminance levels in spaces is costly and

[2]See: https://www.trendcontrols.com/en-GB/bmssystem/Pages/default.aspx

[3]The exceptions are museums, galleries, heritage spaces etc. where light levels are monitored for conservation purposes. However, the technology employed for these specialist applications is not suited for widespread deployment in more everyday spaces such as schools and offices.

often impractical given the conspicuous nature of the devices, of which few if any have been designed with the desired characteristics (see Appendix A).

2.1 Direct measurement of the daylight factor in a real building

One of the many claimed advantages of the daylight factor over any climate-based daylight metric is that it can be measured in an actual space [12]. In principle, it can be a relatively straightforward matter to measure internal illuminance in a space, together with a corresponding measurement of an unobstructed external illuminance under overcast sky conditions. In practice however, various practicalities and confounding factors can make the reliable measurement of a daylight factor difficult if not impossible. The illuminance under overcast sky conditions can vary quite significantly due to often imperceptible (to the eye) changes in the cloud density, which is constantly changing. This is easily verifiable using a light meter. Thus measurements of internal and external illuminance really need be taken simultaneously [13]. For any urban setting, taking a measurement of unobstructed external illuminance could present its own difficulties. Ideally, one would require access to the roof of the building under evaluation, and hope that a vantage point could be obtained where there was no significant obstruction of the sky vault from neighbouring buildings. A significant confounding factor, one not easily overcome, is that only a small proportion of actually occurring overcast skies match the luminance distribution of the CIE standard overcast sky. Furthermore, it is impossible to judge by eye and measurements of horizontal illuminance when a real sky even roughly approximates the CIE standard sky luminance pattern. Failure to ensure that measurements were in fact taken under a real sky which is a reasonable match to the CIE standard overcast sky luminance pattern will almost certainly result in significant errors [14]. Note, the preceding relates to the difficulty in measuring a daylight factor value at one point in a space. Any attempt to validate a prediction for the average daylight factor will require a large number of daylight factor measurements across a grid of sensor points.

In practice, it would appear that determination of the daylight factor in actual building spaces by direct measurement of internal and external illuminance values is only very occasionally carried out:

> *Actual measurements of daylight factor are rarely made in consultancy practice. Some consultancies do not have the equipment required to do this. BRE does, but we have rarely been asked to carry out this type of measurement in consultancy practice (we have undertaken these measurements in research projects).*[4]

Reliable measurement of the daylight factor in a real space under real skies is in fact rather more difficult then it might appear from some guidance in the literature [14].

2.2 Derivation of the daylight factor by indirect means

In a recently published evaluation of daylighting in older people's housing, A. Lewis describes the determination of daylight factors in real spaces as follows [15]:

> *During the survey, average daylight factors were calculated for the living room, kitchen and bedroom of each dwelling, using the formula developed*

[4] Dr. Paul Littlefair, Building Research Establishment, Garston, Watford, UK (private communication 09/12/15)

> *by the Building Research Establishment (BRE) for light on a horizontal working plane at desktop height. The sky component was obtained using a dot diagram placed over a fisheye photograph . . .*

So it would appear that 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. 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 illuminance measurements. Indeed, it would appear that this approach is rather more likely to reveal the real cause(s) for differences between predicted and measured daylight factors. Assuming, of course, that one could reliably measure a real daylight factor in the first place. It would appear that some of the CBDM sceptics set the bar for CBDM validation rather higher than that which is generally the case for the validation of daylight factors in real buildings.

2.3 Climate data: standardised and actual

Standardised climate files contain unique patterns of measurements (e.g. direct normal illuminance) that will never repeat in precisely the same way that they appear in the data. Standardised files are usually compiled from individual months taken from several years of monitored data. Accordingly, it would be a pointless exercise to compare, say, a week or a month of predicted illuminance values (derived from standardised climate data using CBDM) with measurements taken during the same time period (e.g. the month of May) in an actual year.

Even with the full calendar year of measurements the prevailing patterns in *experienced* conditions could differ from those in the standardised climate file due to inter-annual variability. The same is of course true for the much more established practice of dynamic thermal modelling. However, one would expect annual summaries for overall performance measures to be broadly similar from one year to the next since the effects of unique patterns in the data become much less significant when a full year is considered.

2.4 CBDM Metrics and occupant behaviour: real and simulated

A key decision in any CBDM evaluation is whether to include or exclude the effect of building occupants operating shading devices, e.g. venetian blinds, since their use can greatly affect the outcome. An evaluation without occupants discloses what may be termed the intrinsic or asset daylighting performance of the building or space. Uncertainties in behavioural models notwithstanding, a prediction of performance for the occupied building *should* be closer to that of the actual building when it is in normal use. That, unfortunately, is an as yet unproven hypothesis. In a practical evaluation, cutting straight to the prediction for the occupied building may result in the designer missing out on opportunities to improve the intrinsic daylighting potential of the building since this might be masked by uncertainties present in the probabilistic models of occupant behaviour. The uncertainties in occupant behaviour are significant for individual side-lit office spaces, and they can become overwhelming for larger open-plan spaces where the permutations for shade deployment – and consequent impact on daylight provision – become enormous.

The majority of spaces in a building will require use of a shading device at some time or other to control the ingress of daylight. The frequency of deployment of shading devices will depend in large part on how well the basic architectural form of the building serves to temper the luminous environment of the internal spaces. The degree to which this can be achieved is determined by the massing properties of the building and its context. The schematic diagrams shown in Figure 1 illustrate two extremes of architectural type. The 'hi-rise block form' is of course a very common type of commercial building. For the typical office block there is limited scope for the fixed architectural form to offer effective shading from excessive daylight levels. For these buildings, the occupants in spaces which receive direct sun will have the greatest requirement for the use of blinds/shading, either manual or automated. Low-rise buildings with just a few floors have the greatest potential for good intrinsic daylighting since the fixed form can be articulated to incorporate any number of daylighting strategies (e.g. brise-soleil, rooflights, light-wells, light shelves, deep window reveals etc.) often in combination, to shade and redirect daylight. Between these extremes is a continuum of building and space types offering varying potential for the fixed form to temper the luminous environment.

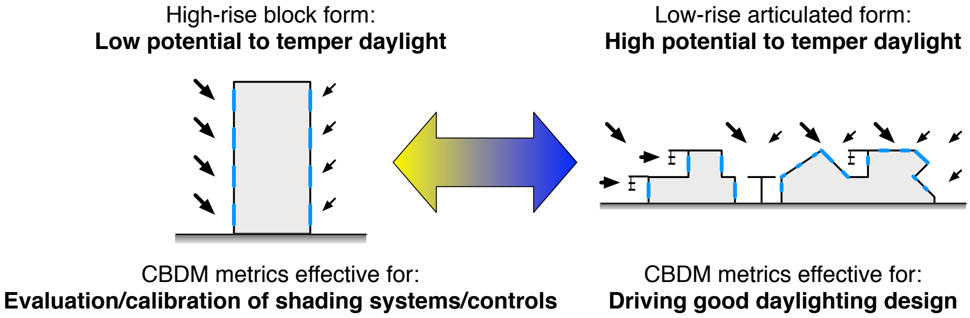

Figure 1: Potential for the fixed form to temper the luminous environment

The simplest and most common form of shading used in non-domestic buildings (i.e. user operated blinds) turns out to be one of the more challenging 'optical' devices to model in a daylight simulation. Optically, a venetian blind is a type of complex fenestration system (CFS) since there is no straightforward relation between incident and transmitted light that can be determined *a priori* from simple, e.g. analytical methods. In addition to the complex optical properties of commonplace shading devices, there is the considerable uncertainty regarding their use by building occupants. Some will frequently adjust the blinds to eliminate direct sun whilst admitting diffuse light, others will lower the blinds to their maximum extent and close the slats – an action which invariably results in the lights being switched and left on.

To summarise, the prediction of daylight through commonplace, moveable shading devices such as venetian blinds is highly problematic. And, given all the uncertainties noted above, any metric that is dependent on these complex interactions must have some qualification regarding its validity as a measure of actual performance. Automated shading systems are another matter, and the qualifications previously noted might not apply to, say, variable transmission glass (e.g. electrochromic glazing) which has easy to model light transmission properties, i.e. purely specular [16].

Another reason to be sceptical regarding the modelling of occupant behaviour is the lack of illuminance data in real, occupied spaces to compare against. The simple truth is that the *operational* daylighting performance of residential, classroom and office spaces is, in almost all cases, an unknown quantity. And it will remain so until the monitoring of illuminance becomes as routine as it is for air temperature.

The schematic shown in Figure 2 outlines the scope / confounding factors for various routes to validation and summarises much of the argument given in this section.

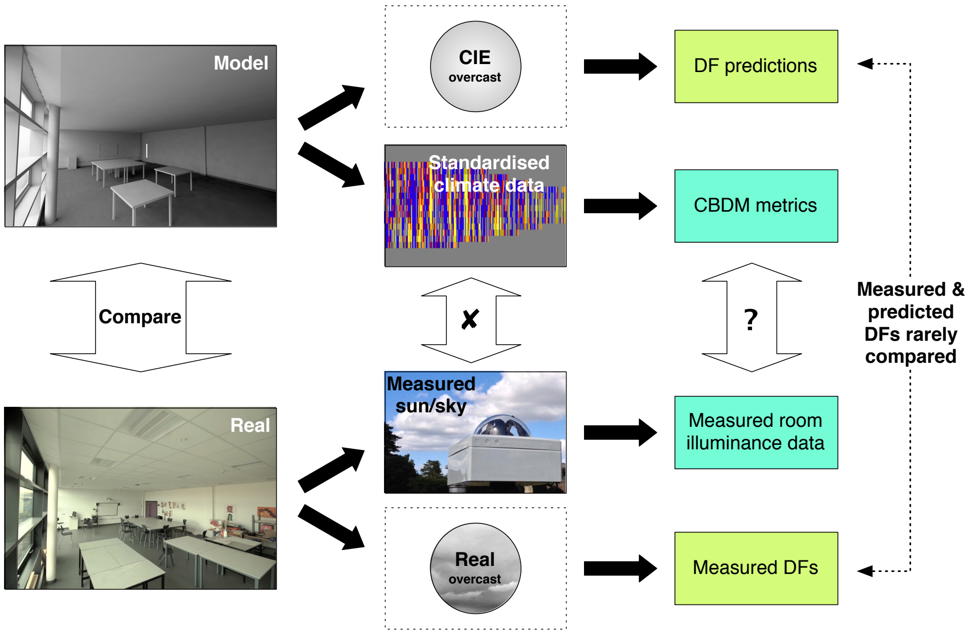

Figure 2: Modelled and real scenarios – the scope for validation

3 A Proposal for Validation of Climate-Based Daylight Metrics

In this section the authors outline a proposal to validate CBDM metrics in a real school classroom setting. The classroom is one of four that have been monitored as part of a mixed methods study to relate the subjective impression of daylight performance to objective measures of the luminous environment [17]. A photograph of one of the classrooms together with a simulated rendering of the space were shown in Figure 2. For any occupied space, not a least a school classroom, it is practically impossible to obtain a reliable time-series of illuminance measurements taken at desk height without cordoning off the area around the sensor – an intervention that would be difficult to both approve and enforce. It becomes necessary therefore to consider other means, i.e. proxies from which illuminance on the horizontal might be derived. Illuminance measured on a vertical wall – at one or more points – could serve as proxy for horizontal illuminance at desk height if a sufficiently robust relation between the two could be demonstrated. This approach, in principle, is plausible provided that very steep illuminance gradients are excluded from the evaluation. In practice, that means avoiding any instances of direct sun on either the vertical (i.e. wall) or horizontal (i.e. desk) surfaces. The validation of *Radiance* using the BRE-IDMP dataset showed that instances involving direct sun on or very near to an illuminance sensor introduce a number of largely insurmountable confounding factors that are nothing to do with the intrinsic accuracy of the simulation tool [4]. For example, even the tiniest divergence between real and model geometry could result in the sensor predicted to be in shade when in fact it was in full sun, or vice versa. Either way, such occurrences introduce enormous errors.

As noted in Section 2, illuminance sensors suitable for deployment in occupied spaces are not yet readily available (see Appendix A). To overcome this limitation the authors intend to derive illuminance from measurements of luminance taken using high dynamic range (HDR) imaging – an approach recently demonstrated in a heritage building [18]. The classroom setting that will be used is described below. The simulation-based tests reported below indicate that wall illuminance can indeed serve as a useful proxy for horizontal illuminance.

3.1 Measuring illuminance in occupied spaces using HDR

For the mixed methods study two classrooms from each of two post-16 schools in Leicestershire were chosen. Classroom selection was such as to include variations in floor and glazing area, class layout, orientation, aspect, view obstructions and shading controls. In terms of use, effort was made to select classrooms where more commonplace 'sit down' teaching occurred, e.g. excluding studio, laboratory and workshop spaces. In one of the schools, the classrooms were chosen based on a teacher survey conveying the general consensus on the best and worse daylit classrooms. In the second, the selection was at the discretion of the researchers and such as to include as much variation as possible amongst the case studies.

In each classroom, the HDR monitoring set-up was composed of a Canon EOS digital SLR camera with a 10–18 mm wide-angle lens (set to 10 mm) tethered to a 'headless' Mac Mini with 1TB hard-drive.[5] This was installed on a high point at the back of the room to capture the wall that carries the smart-board as well as an adjacent wall. Starting 3rd April 2015, HDR captures occurred daily from 09:00 to 15:50 (17:50 for the second school) every 10 minutes. Complimentary data included illuminance values recorded every minute by a Hanwell ML4000 light meter logger on a constant spot (from 16th November onward) for calibration purposes. External incident solar radiation data was also monitored with a 10 minute resolution (from 22nd July onward) using an SPN1 Sunshine Pyranometer and BF5 Sunshine Sensor installed in the vicinity of one of the schools (both sensors from Delta-T Devices, Cambridge, UK).

For the next stage of the study – currently in progress – a time series of illuminance values across various wall surfaces will be derived from the HDR images.

3.2 Wall illuminance as a proxy for horizontal illuminance

In this section the authors use lighting simulation (i.e. CBDM) to demonstrate that vertical wall illuminance can serve as a proxy for horizontal desk illuminance. The modelled classroom was based on one of the four used in the above-noted study (see rendering in Figure 2). This classroom is a side-lit space, 11.2 m wide, 7.9 m deep and 3.0 m floor to ceiling. The real orientation and location of the space are not relevant for the purpose of this preliminary study, therefore the reference climate data was the EPW file for London Gatwick, sourced from the EnergyPlus website. The analysis was repeated for several orientations and the optical properties assigned to the modelled surfaces were the standard ones: 0.2 for the floor and external ground, 0.5 for the walls and the window frames, 0.7 for the ceiling.[6] The simulation was carried out using the *Radiance* 2-phase CBDM method with the following ambient parameters: `-ab 5 -ad 100000 -lw 1e-5` [19].

[5] A headless computer is one that will function without screen, keyboard, etc.

[6] Reflectances that more closely match those for the actual classroom will be used for the next stage.

The aim of this exercise is to draw a correlation between the illuminance on the horizontal plane and the illuminance on the vertical walls, specifically the walls that are captured in a series of HDR images at fixed intervals throughout the day, so that a further correlation between the luminance recorded by the HDR captures on the vertical walls and the horizontal illuminance can be investigated for the next stage. For the simulation, a horizontal sensor was placed in the centre of the room, while six vertical sensors were placed on the shorter wall and 10 on the longer wall.

For this preliminary study, it was decided to consider only the diffuse component of daylight by extracting only the diffuse horizontal irradiance from the climate file when generating the sky luminance distribution. This is a necessary constraint, as an accurate representation of the strong directionality of sunlight would require a perfect match between the modelled space and the real world classroom, in terms of geometry, optical properties, location and orientation.

For each of the two walls, the correlation between the resulting illuminance values at the horizontal central sensor and the vertical illuminance averaged across the wall is reported in Figure 3. The first Figure represents the results obtained at every hour of the year when the fenestrated side of the room is looking towards North and shows the best correlation between horizontal and vertical illuminances, with a coefficient of determination of 0.97 for both walls. For both cases, the correlations are believed to be sufficiently good to warrant proceeding to the next stage of the study, which is outlined below.

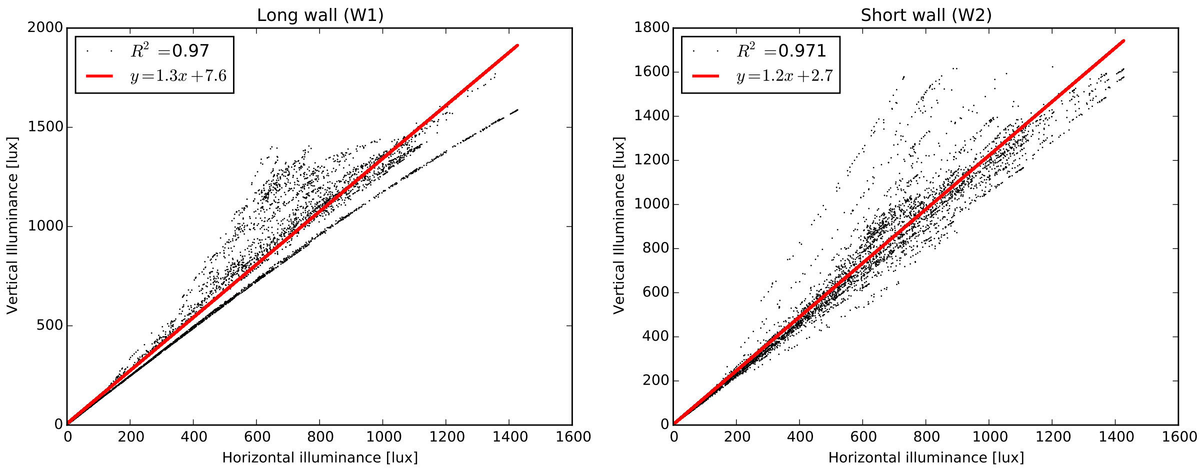

Figure 3: Linear correlation between the horizontal illuminance at the centre of the room and the vertical illuminance along two walls when the windows are oriented towards North.

3.3 Outline of the next stage

For the next stage, the objective will be to compare HDR-derived measurements of illuminance recorded in the classroom space with simulated illuminance values using sun and sky conditions based on simultaneous measurements of direct and diffuse horizontal illuminance. For this, the sky luminance pattern will be generated using a suitable sky model. Measured sky luminance distributions are to be preferred for the most rigourous validation work [4]. However, studies have shown that reasonable accuracy for illuminance predictions can be obtained using sky models [20]. If reasonable correspondence can be made between measured and simulated illuminances under actual sun and sky conditions, then that would support the proposition that CBDM metrics are indeed illustrative of the daylighting performance of the fixed building form (i.e. without the operation of blinds/shades).

Part and parcel of the evaluation will be a comparison of real and assumed reflectance values for key surfaces in the classroom, e.g. the walls, the floor and the ceiling. As is evident from the photograph and rendering shown in Figure 2, an occupied space will differ from that which is typically assumed for the model created for the simulation. It seems quite likely that occupied spaces will, in the main, have surfaces with a lower effective reflectivity than is commonly assumed for modelling purposes – that applies equally physical/scale models as well as simulation models [5]. A recently demonstrated technique has shown how it is possible to accurately measure the effective reflectance of real walls containing arbitrary variations in surface finish (e.g. posters, notices, etc.) using an HDR-based method [21]. The luminance values in an HDR image are used to derive the per-pixel values of surface reflectance, i.e. an albedo map. The effective wall reflectivity in the classroom will be determined using this technique.

4 Summary

Validation of predicted measures of daylight performance in actual buildings has proven to be a challenging prospect. In fact, it always has been irrespective of the measure used, e.g. daylight factors or CBDM metrics. However, with daylight factors the notional simplicity of the basis of the metric, and consequently the apparent ease with which it can be measured/tested, have proven to be illusory. Actual measurement of daylight factors in real buildings is rarely carried out, and the confounding factors are many and difficult to correct for. Compounding the problematic nature of any attempt to validate daylight performance is the woeful lack of any data on actual measures of illuminance in real, occupied spaces. Anyone attempting such an endeavour is effectively 'starting from scratch' with regard to pre-existing data – in contrast to, say, thermal parameters where there is a veritable glut of data for occupied building spaces waiting to be examined.

As noted in Section 2, the bar has been set high for this evaluation. In order to attempt a 'real world' comparison of measured and modelled illuminance values, it has been necessary to devise novel means to record basic luminous parameters (e.g. illuminance) in occupied spaces. Nevertheless, the authors are fortunate that a number of advances in daylight metrology have taken place recently. These will be applied to the scenario described above and reported on in due course.

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Appendix

A Monitoring illuminance in buildings: a sensor specification

A list of the desired characteristics for a sensor to measure illuminance are as follows:

a. Reasonably accurate – measure lux over a wide range (e.g. 0 to 100,000 lux) with an accuracy of at least ±20%, preferably ±10%.
b. Affordable – the cost of individual sensors should be no greater than £50, preferably a fair bit lower.
c. Reliable – should be able to function autonomously for long periods.
d. Smart – sensors should be able to integrate with existing data collection systems (e.g. BEMS), and also allow for the ad hoc downloading of data to, say, smartphones.

The spatial variation in natural illuminance levels across a space can be an order of magnitude or greater. Thus it is desirable to monitor illuminance at more than one point. Furthermore, a measurement of illuminance could easily be rendered useless if the device is poorly located. It would seem preferable therefore to install any illuminance measuring device *after* the space has been fixed, fitted and decorated. And perhaps 'occupied' should be added to the list also since, the re-arrangement of furniture and/or the placement of posters on the walls could interfere with the measurement of illuminance. An additional desired characteristic therefore is that the device should be powered by its own battery and be largely autonomous.

A device that fits most – but not all – of the above characteristics is the Texas Instruments SensorTag. The SensorTag contains a number of sensors now commonly found in mobile phones/tablets in addition to one for 'ambient light' which uses the OPT3001 sensor, Figure 4. The spectral sensitivity of the OPT3001 is a close match to the sensitivity curve for the human eye (i.e. the $V(\lambda)$ curve). And it also has a high dynamic range. However, as is evident from the photograph shown in Figure 4, in this configuration the OPT3001 is housed in a clear plastic housing, and so it is almost certainly the case that the response will not be cosine corrected – a requirement to measure lux correctly. Hence, the label 'ambient light sensor', i.e. some light quantity but not lux. It is possible however that the SensorTag device – or something similar – could be inexpensively adapted to measure illuminance (i.e lux values) to an adequate level of precision. Note: the authors are not endorsing this or any product, we merely wish to bring to attention promising technology that could form the basis of a smart, low-cost illuminance sensor for the routine monitoring of light levels in buildings.

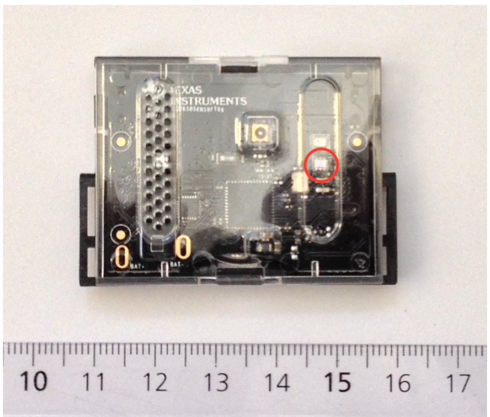

Figure 4: Texas Instruments SensorTag – OPT3001 sensor circled in red