The implementation of natural lighting for human health from a planning perspective

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This paper makes the case that a significant factor in the failure to ensure adequate daylighting performance for interior spaces is often due to the inadequacy of methods used at the early stages of planning. All of the methods currently used for daylight/sunlight planning share common failings: they cannot make meaningful estimations of performance at the outset, nor can the methods used be extended/refined to overcome these failings. Thus, it is argued, a new approach is required.

The paper gives an overview of the history and development of methods to predict performance; from the conception of the daylight factor to climate-based daylight modelling. The impact of prescriptive planning regulations is described using New York City as the example. The paper concludes with an outline of a new modelling schema which can provide the much needed link between the real-world practicalities of building planning and the need to determine realistic indicators of building performance at the earliest stages of obtaining planning consent.

1. Introduction

1.1 Daylight and human health

There now appears to be a general consensus that regular exposure to daylight is essential to maintain human health and well-being. The earliest connection linking insufficient daylight/sunlight to a recognised clinical pathology (the bone disease known as rickets) was made in 1861–1862.1 More recently, insufficient illumination received at the eye during childhood/adolescent development is implicated as one of the factors causing an enormous increase in the incidence of short-sightedness in teenagers: a ‘myopia boom’.2 To prevent rickets, exposure to sunlight outdoors is needed. The role of daylight insufficiency as a significant factor behind the onset of myopia is not yet fully understood; however, illumination levels that can only usually be achieved outdoors have been suggested.2

With regard to daylight indoors, there is ample evidence that building occupants invariably prefer spaces with windows (providing ‘good daylighting’ and views) to spaces without windows (or with ones that are ‘too small’).3 The reasons why would appear to be multi-factorial, e.g. ‘connection’ to the outdoors, the information provided by the view (including the sense of time), the continuous (daylight) spectrum of illumination, the inherent changeability and dynamics of daylight illumination, etc.4 The complex and inter-dependent nature of these interactions are such that it has proven extremely challenging to quantify the importance of any one of the individual factors. Accordingly, there is little consensus regarding what the general or

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minimum requirements for daylight illumination inside buildings should be.

Commonplace notions of well-being have long been associated with improved measures of human performance: ‘happy’ workers are believed to be ‘better’ workers. Studies relating occupant comfort to (worker) productivity first appeared in the literature nearly a century ago. The environmental parameters investigated were typically temperature, humidity and airflow – factors that were relatively easy to control in air-conditioned buildings. However, it was not until the 1990s that evidence began to appear suggesting that ‘good daylighting’ could result in improved measures of alertness, productivity and academic achievement. Also in the 1990s it was discovered that the eye possesses an additional non-rod, non-cone photoreceptor named photosensitive retinal ganglion cells (pRGC). The pRGC communicate light-induced signals to the suprachiasmatic nuclei (sometimes referred to as the ‘circadian pacemaker’) in the anterior hypothalamus of the brain. Light has measurable neuroendocrine and neurobehavioral effects on the human body, in particular with respect to maintaining a regular sleep–wake cycle that is entrained to the natural diurnal cycle of night and day. These and related discoveries have led to the emergence of a new area for photo-biology research concerned with daylight/light exposure and its, so-called, ‘non-visual’ effects on people. It is now widely accepted that the nature, the patterns and levels of illumination experienced by people have a major effect on their long-term health and well-being.

In many parts of the developed world, people are now spending 90% of their time indoors. As a consequence, and given the weight of evidence emerging from photo-biology (and related disciplines), it is now widely accepted that ‘adequate’ daylight illumination inside buildings is essential to sustain and promote human health and well-being. However, as indicated above, at present, there is little agreement regarding what constitutes an adequate level of daylight illumination, or even if the (yet to be determined) illumination level(s) should be described using photopic measures or one of the recently formulated non-visual/circadian metrics, e.g. equivalent melanopic lux.

Around the time that the importance of daylight in buildings for health and well-being was beginning to be recognised (i.e. the 1990s), new, so-called, ‘climate-based’ computer simulation techniques to predict daylight in realistic architectural spaces were pioneered. These offered huge advances over existing methods, e.g. founded on annual weather file data and using realistic sun and sky conditions. More recently, the daylight performance recommendations in the new European Standard have undergone a significant upgrade to base evaluation on the provision of absolute levels of illumination derived from weather file data. Notwithstanding the development of the new simulation techniques and the possibilities they offer, there is no consensus regarding how – or even if – these techniques should be used at the earliest stages of building design/planning.

The daylight evaluation method used at the early design stage is a major determining factor governing the actual daylighting performance of the resulting spaces, particularly in any obstructed/urban setting. Early design evaluation for planning purposes (e.g. to seek approval for development of a site) typically employs methods that do not account for possible window sizes. It is generally the case that early design daylight/sunlight evaluation methods are founded on techniques that offer little or no opportunity for ‘seamless’ progression to more refined/revealing evaluation methods, e.g. climate-based daylight modelling. In other words, it is difficult – if not impossible – to make meaningful estimations of likely daylighting potential of the
completed buildings from using the early design/planning methods because critical factors such as the window design are not accounted for. Whilst evidently less than ideal, the present state of affairs is understandable, given the developmental history of daylight prediction techniques and the, often competing, interests of the various stakeholders. For example, those carrying out early design evaluations favour simplicity. Whereas any consideration of daylighting potential (either for amenity or health and well-being) will require some form of inherently more complex performance evaluation.

This paper aims to describe how the present situation came about, and to offer a practical remedy to the problems identified. This Introduction concludes with a very brief overview of the history of the daylighting design of buildings. The section that follows focuses on quantitative measures of daylighting performance and how the development of prediction/evaluation techniques evolved from the earliest mention of the daylight factor (possibly in 1895) to climate-based daylight modelling a century later. The section includes discussion (and opinion) on the practicalities and reliability of the various modelling techniques. It uses the project ‘Daylighting the New York Times Building’ as an (exceptional) example of what can be achieved with daylight simulation given sufficient resources. Mention is made of the inclusion of various measures in guidelines and standards. Section 3 presents a brief survey of daylight/sunlight planning guidelines and gives the New York 1916 Zoning Resolution as an extreme example of a prescriptive restriction that had a profound and lasting effect on the urban density of the city. The section concludes with a viewpoint making the claim that, notwithstanding the development of powerful simulation tools, existing approaches to performance evaluation do not meet the practical requirements necessary for planning purposes. The penultimate section opens with an attempt at a synthesis of the preceding material. Its goal is to identify the reasons why the means to bridge the gap between planning and performance have, until now, remained elusive. The main part of that section presents a brief overview of a newly formulated approach to daylight/sunlight prediction called Aperture-Based Daylight Modelling (ABDM). Radically different in conception and application to existing approaches, ABDM was conceived with the express aim of bridging the aforementioned gap.

1.2 Daylighting design of buildings

The first humans to live in settled communities spent the majority of the daylight time outside, and the purpose of the earliest shelters (in cool/temperate climates) was primarily to protect from the cold, wind and rain. The earliest ‘windows’ were simply holes in the wall or roof of the dwelling which provided some daylight, but mainly ventilation. The need for a light transmitting medium that would protect from the elements was first met by translucent materials such as flattened hides and thinly sliced sheets of marble. These materials did not allow for views and either lacked resilience or were difficult to manufacture in pieces larger than a few tens of centimetres across. It was with the invention of glass that the story of daylighting design for buildings truly begins. The earliest known glass objects were beads manufactured about the third millennium BC. However, the first recorded use of glass for windows was not until approximately 100 AD by the Romans. The largest panes that could be manufactured were still fairly small. The use of vertical and horizontal dividers increased the size of areas that could be glazed, since small pieces of glass could be combined to create large windows. Substantial dividers could additionally form part of the load bearing structure.
Glass windows became common in homes in the most developed parts of Europe only in the early 17th century. With the advent of improved production techniques in the following century, the cost of glass became less of a limiting factor in its use, although its relative cost compared to other building components was still fairly high. Notwithstanding the high cost of glass, the real cost of artificial light (i.e. as a proportion of the overall household expenditure) was several thousand times what it is today on a per lumen of light basis.\(^{20}\)

The variation of the window area according to the size/function of the space and degree of external obstruction became commonplace as building densities increased. This often resulted in the ground floor rooms having the largest windows, with the window area gradually decreasing for the floors higher up. In the UK, this arrangement is generally referred to as the Georgian window pattern, although its use extended well beyond the Georgian era (i.e. 1714 to 1830).

Prior to the 1900s, buildings generally incorporated features that evolved from the need to temper the internal conditions in response to the prevailing climate for that locale. In hot climates with a high propensity for sunshine, buildings would be designed to include elements of solar control either by passive and/or active means. For example, on sun-exposed facades, there would be small windows set in deep reveals to provide self-shading (passive control), or perhaps larger windows with moveable shutters (active control). In less hot/sunny climates, window apertures would tend to be larger and solar control less of an issue – although there would be other concerns such as heat loss. Thus, all buildings contained to varying degrees features in their design that were climate-adapted, and which, over time, became an intrinsic part of that locale’s vernacular architecture.

The latter half of the 20th century witnessed a globalisation in architectural form.

The highly glazed office tower became the most conspicuous symbol of industrial progress, and hence an inspiration for architects and designers worldwide – regardless of their local climatic conditions. The confluence of a number of economic, technological and aesthetic factors working together served to establish the highly glazed office tower as the preeminent urban building form. Key amongst these factors were:

- The development of curtain wall technology.
- The invention of the float glass technique that allowed the manufacture of large sections of high-quality glazing at relatively low prices.
- The refinement and wide-spread adoption of fluorescent lighting as a replacement for incandescent lighting.
- The desire to reduce capital and running costs through higher occupant densities in deeper-plan spaces.
- The development of high-capacity air handling and air conditioning systems that eliminated the necessity for ventilation or cooling by natural means.
- A trend in modernist architecture which became preoccupied with vaguely defined notions of ‘light’ and ‘transparency’ in the built form – the realisation of which was invariably highly glazed buildings.

Designers typically rationalised the use of large glazing areas in terms of their daylight provision, but often it was more likely the pursuit of style. Aside perhaps from the possibility of a view to the outside, the daylighting benefit to the majority of occupants in a deep plan space was not great since few would be close enough to the perimeter to gain any direct benefit in terms of daylight provision. Furthermore, the daylighting potential of highly-glazed buildings was often not realised because the manually-operated shades/blinds needed to control direct sun were typically left closed long after the external condition had
changed. This is the case in fairly temperate climates such as the UK and Northern Europe, e.g. this photo of the Saules Akmens building in Riga (Latvia) taken on a not very sunny day, Figure 1. The sub-optimal use of manually operated blinds is worse still in sunnier locales.

2. Daylighting performance: Measures and targets

This section surveys the historical development of quantitative measures of daylighting performance, from the origins of the daylight factor to the development and application of climate-based daylight modelling.

2.1 Sky factor and daylight factor

What is commonly referred to as the Waldram method is founded on the notion of the sky factor. The sky factor \( SF \) is the ratio of the illumination on a horizontal surface at a point in a space \( E_{in} \) to the unobstructed external horizontal illumination \( E_{out} \), usually expressed as a percentage

\[
SF = \frac{E_{in}}{E_{out}} \times 100\%
\]

Figure 2 Sky factor and daylight factor

The sky is taken to have uniform luminance, i.e. the same apparent brightness everywhere on the sky vault, Figure 2(a). The assumption of uniform luminance was intended to represent a heavily overcast sky. This quantity is still in use in England where it serves as the basis of the ‘rights of light’
procedure, i.e. the Waldram method noted above. A ‘right of light’ is an easement acquired by one party and applied to one or more windows in a building owned by that person. If some windows have enjoyed a prospect which has provided daylight without interruption for a period of 20 years, then the window(s) may have acquired a legal right of light (there may also be other factors involved). Any reduction of that daylight beyond a certain degree caused by a proposed building (overshadowing the windows) could result in an injunction preventing its construction. Most rights of light cases are settled prior to court hearings, and substantial sums are often involved. Neither reflected light nor attenuation from any glazing are accounted for in ‘rights of light’ evaluations. And the window aperture is usually taken to be fully open, i.e. no window framing of any kind is present. Note, the sky factor level decided by Waldram in the 1920s which is used to delineate the boundary between acceptable and unacceptable daylight is 0.2%. This so called ‘grumble point’ equates, in real spaces, to low levels of absolute daylight illumination. Waldram’s methodology has undergone forensic scrutiny in a series of papers over the last two decades. Notwithstanding the extensive criticism received in recent years, the Waldram method remains (in England) the basis of the only legally enforceable right to (at least some) daylight illumination.

Although it is customary to calculate the sky factor on an internal horizontal surface, there is no reason in principle why the sky factor could not be determined on, say, an external vertical surface. Note, the commonly used in planning, vertical sky component (VSC) is similar to the Waldram sky factor, the key difference being that the VSC is calculated using a non-uniform sky brightness pattern, i.e. the CIE standard overcast sky used for the daylight below (see below).

Similar to the sky factor, the daylight factor $DF$ is defined as the ratio of the internal horizontal illuminance $E_{in}$ to the unobstructed (external) horizontal illuminance $E_{out}$, Figure 2(b). As with the sky factor, the daylight factor is usually expressed as a percentage

$$DF = \frac{E_{in}}{E_{out}} \times 100\%$$ (2)

There are, however, key differences as follows:

(i) The CIE Standard Overcast sky luminance pattern is used (instead of the uniform luminance pattern).

(ii) The internal illuminance now includes all reflected light, e.g. from the ceiling, walls, floor, etc. including externally reflected light.

(iii) The reduction in light due to the window transmission properties is accounted for, as is the shading effect of window framing.

As with the sky factor, the daylight factor has the following properties:

- It does not account for the sun, e.g. cannot be use to assess solar shading.
- It cannot account for the effect of scene orientation, i.e. the daylight factor is the same whatever direction the window(s) is facing (provided the entire scene is rotated).
- It does not account for climate/location, i.e. daylight factor is the same wherever the building is intended to be.

The daylight factor value can be considered to be a measure of the ‘openness’ of the space to daylight illumination under a particular overcast sky condition.

The basis for the formulation of both the sky factor and the daylight factor can be traced back, in publication, to 1911 and Alexander Pelham Trotter’s book:
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The illumination of a room by ordinary daylight depends on three conditions. First, the external character of the source of illumination, viz.–the time of day, the time of year, the kind of weather or sky; second, the area and aspect of the windows; and third, the colour or reflecting power of the walls, ceiling, floor, and contents of the room. The first of these conditions is so variable that it must be eliminated. The second and third being practically constant for any room, may be measured together and expressed as a coefficient.

Whilst Trotter does not mention explicitly the transmission properties of the glazing, these would be accounted for in any measurements that might be taken to determine the ‘coefficient’ of any particular room.

I have succeeded in eliminating the first of these conditions by adopting as a unit, of which this coefficient is a fraction, the illumination which would be produced at the spot in question, if all buildings in the neighbourhood were demolished, and the illumination were produced by light from a uniformly grey sky.

Trotter notes in the book that he ‘first devised this system of measurement of daylight illumination in 1895’, but that ‘but no practical work was done until P. J. Waldram took it up twelve years later’. Trotter goes on to give a list of ‘coefficients’ for notable buildings measured by Waldram. In the 1951 Trotter-Paterson Memorial Lecture, J.W.T. Walsh refers to the ‘coefficients’ as ‘daylight factors’. It seems likely that what became the commonplace usage of the daylight factor approach was largely established by the methods described in HMSO and BRS (now BRE) publications in the 1940s and 1950s.

Whilst the daylight factor is generally taken to be an evolution of the sky factor, the precise reason for the switch from the uniform sky to CIE overcast sky pattern does not appear to have ever been clearly argued, other than the oft quoted statement that the overcast sky offers a worst case condition. Superficially, this may appear reasonable on the basis that a minimum standard should assume a worst-case condition. On closer inspection, however, this rationale is less sound than it first appears. The original intent for using the ratio of internal to external illumination was to rate the space independent of the actually occurring daylight conditions. Thus, the initial choice of the uniform sky was not only a good one, but arguably the best choice that could be made since, any other sky type would necessarily bias the evaluation (and any outcomes from using it) to the characteristics of that particular sky luminance pattern. The measurements taken by Moon and Spencer which served as the basis for the CIE Standard Overcast Sky were reported in 1942. It is now known that only a small proportion of actually occurring overcast skies approximate the CIE formulation. The CIE Standard Overcast Sky is in fact – to quote Enarun and Littlefair – an ‘extreme’ case of overcast sky.

For the purpose of daylight planning, guideline document BR 209 (see Section 3.1 below) recommends the use of the vertical sky factor on a facade. This is the direct light received on the vertical, relative to the horizontal, under CIE Standard Overcast Sky conditions. Where there are no other obstructions, the maximum possible vertical sky factor is approximately 40%, even though, of course, exactly half of the sky dome is visible from any surface on that facade – a consequence of the CIE Standard Overcast Sky formulation. Had the original uniform sky been used, then the maximum possible vertical sky factor would be 50%.
Given that we now know the CIE formulation describes what is in fact a rarely occurring sky luminance pattern, a uniform sky is arguably a more rational basis – certainly for planning. Put rather more provocatively, the adoption of the CIE Standard Overcast Sky as the basis for guidelines and standards was, in this author’s opinion, something of a blunder. It would have been better to keep the uniform sky, until at least the advent of climate-based daylight modelling. And, even after climate-based daylight modelling became established, there may be good reason to continue using the uniform sky for certain purposes.

2.2 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. 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. That study showed that illuminances predicted using the Radiance system could be within ±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. 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 own daylight coefficient implementation (known as the ‘Four Component Method’) was shown to have comparable high accuracy to the standard Radiance calculation.

In the last 20 years, CBDM (invariably using some form of Radiance) has been employed on numerous projects/studies to evaluate long-standing and novel daylighting problems. Use of CBDM is now commonplace amongst daylight designers and consulting engineers, whilst academics continue to extend the range of applicability and, importantly, test the reliability of the predictions from the various CBDM formulations, e.g. the two-phase, three-phase and five-phase Radiance methods, etc. Easy-to-use CBDM tools have ‘visual’ interfaces that no longer require the user to learn scripting/coding or indeed to have an understanding of how Radiance works. These tools have made complex, multi-factorial/parametric daylighting evaluations relatively easy to achieve. An unfortunate downside of the low ‘cost of entry’ (with regard to required expertise) is the risk that the simulation engine is treated as a supplier of unimpeachably accurate results.

2.3 Landmark CBDM: Daylighting the NYT building

Carried out largely during 2004–2005, ‘Daylighting the New York Times Building’ was a measurement and simulation project of both unprecedented scale and detail. It expanded the limits of what was considered possible with simulation, and perhaps even today (a decade and a half later), it has not been surpassed for the scale and intensity of
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The exquisitely detailed 3D model that was created for the daylight simulations is shown in Figure 3 (upper three renderings differing by factor ×10 zoom each time) – the fourth image is a photograph taken in 2018.

Simulations were used for a variety of purposes, from understanding the effects of urban shadow on shade usage to assisting with pre-calibration of photosensor sensitivity in a complex daylit interior environment. Notwithstanding the dramatic effect of the ceramic bars on the appearance of the building, their purpose was not to temper the internal luminous environment – that would be provided by a motorised/automated top-down roller shading control system. Automation of blinds was essential to avoid the ‘blinds down / lights on’ behaviour that was commonplace in highly glazed buildings with manual blinds operation (Section 1.2).

Annualised (later called CBDM) simulations were conducted to assess visual comfort conditions, daylight provision and availability of view. The intention was to design a control system for the automated roller shades that would achieve a highly favourable balance between offering protection against glare and the provision of daylight/views. Simulations were made with the occupants’ seated field of view located in a worst-case position close to the window in a direction normal to the window, Figure 4(a). Evaluations were carried out on multiple floors to cover those largely shaded by neighbouring buildings (e.g. floor 6) and those with a largely unobstructed aspect (e.g. floor 26). Simulated field of view images were generated from every viewpoint (on multiple floors) at a time-step of 15 minutes using sun and sky conditions derived from weather files for the locale – a single point-in-time image from one viewpoint is shown in Figure 4(b). The CBDM simulations produced 140 Gb of output which needed to be post-processed, analysed and reduced into meaningful metrics.

Did it work? In a post-occupancy evaluation (POE) reported in 2013, it seems that the occupants were largely pleased with both the levels of daylight provision and the glare...
control operation of the automated blinds. This gives confidence that simulation can have a positive impact on building performance and occupant comfort. However, the POE cannot be taken as proof that the real building occupants (over 12 months) actually experienced something approximating the annual profiles of illuminance (on their desks) and luminance (field-of-view) generated by the simulation. That would require a long-term, enormously expensive monitoring and validation study.

2.4. CBDM and the Education Funding Agency

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 (UDI) metric. The UDI metrics are measures of the annual occurrence of daylight illumination within certain ranges, e.g. between 100 and 3000 lux. The presence of an upper limit penalises the occurrence of excessively high daylight levels in the space, e.g. those associated with direct sunlight. 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.

This was a bold step, but why was it taken? The Building Schools for the Future (BSF) scheme in the 2000s was an ambitious and costly investment programme to build much needed new (mainly secondary) schools. However, the quality and design of the first wave of BSF schools were heavily criticised in the press: ‘£35bn revamp will produce generation of mediocre schools’. There were many examples of poor design and commissioning resulting in overheating, with even cases of 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’. In particular, these BBC News reports note further 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’; ‘...new buildings where much glass was used in the design’.

Around the millennium, a number of reports regarding daylight and performance...
were published that became highly influential. Notable amongst these was ‘Daylighting in schools: An investigation into the relationship between daylight and human performance’ by the Heschong Mahone Group in 1999. Part of the problem with the BSF designs appeared to be that the message regarding the importance of ‘good daylighting’ in classrooms appeared to be getting across – but that it was being implemented crudely. For example, statements such as this in design guidelines at the time were fairly typical: ‘maximising the use of daylight in order to improve student performance...is an absolute imperative’. A half-century or more of (often routine) application of the daylight factor method had led to a more is better mindset: ‘good daylighting’ was taken to mean ‘higher daylight factors’. Perhaps this was inevitable given that the daylight factor was the only quantitative daylighting measure in common usage. Attempts to incrementally advance the DF method using so-called ‘clear sky options’ (e.g. LEED, ASHRAE 189.1) were less than convincing.

The use of CBDM necessarily includes sunlight in the assessment of daylight, and the UDI metric penalises excessive levels of illumination (often caused by sunlight). Whilst this author was not a party to the EFA deliberations regarding the requirement for CBDM (which, unfortunately, were never made open for peer review), it does seem likely that some or all of the above – not least, over-glazing in BSF schools – would have figured in that decision to a greater or lesser degree.

2.5 Performance guidelines and targets

From the 1950s, and for the next half-century, daylighting performance guidelines and recommendations were invariably described in terms of the daylight factor, and often just the average daylight factor (ADF) value for the space. For example, British Standard 8206-2 ‘Daylight in Buildings’:

The average daylight factor is used as the measure of general illumination from skylight. It is considered good practice to ensure that rooms in dwellings and in most other buildings have a predominantly daylit appearance. In order to achieve this the average daylight factor should be at least 2%. If the average daylight factor in a space is at least 5% then electric lighting is not normally needed during the daytime, provided the uniformity is satisfactory.

The ADF found favour in part because it could be calculated using a simple equation, thus avoiding any requirement for a 3D model and a daylight simulation program. It was also claimed and generally assumed that a metric founded on the daylight factor would, in principle, be relatively straightforward to verify by direct measurement. However, it turns out that verification of the ADF by direct measurement is both difficult and unreliable, for a number of reasons including the fact that the CIE Overcast Sky pattern is a rarely occurring condition. As noted in Section 2.4, the unfortunate application of a ‘more is better’ mindset with regard to the daylight factor approach was one of the contributing factors to some of the poor design outcomes of the BSF programme.

The new European standard for daylight in buildings EN 17037 is the first major standard founded on the provision of absolute levels of illumination (e.g. 300 lx) rather than relative values such as the daylight factor. The Standard has been adopted by the UK (where it superseded BS 8206-2) and all 27 EU nations, although its adoption in the UK has not been without its critics (and defenders). Nevertheless, the standard has been well received in many quarters. In large part, this is because the use of absolute units of
illumination provides a foundation for the means of, eventually, connecting the recommendations in a daylight standard to the emerging science of light and well-being. The internationally used WELL Building Standard claims that it is the first to focus ‘solely on the health and wellness of building occupants’. Based in the US, the WELL Standard is applied worldwide. Version 2 of the standard released in 2020 adopted the performance evaluation methodology and recommended daylight levels of EN 17037 as an option to demonstrate compliance.\textsuperscript{50}

2.6 Daylight spectra

The colours, or more specifically, the spectra of the various phases of daylight are closely related to the commonplace experience of naturally occurring sun and sky conditions, e.g. clear blue skies, white clouds, red sunsets, etc. Prevailing conditions can be characterised in terms of a correlated colour temperature.\textsuperscript{51} For certain typical sun and sky conditions, there are standardised spectral power distributions.\textsuperscript{52,53} From these, it is possible to estimate the time-varying spectra of daylight from illuminance values in standardised climate data files. Thus, it becomes possible, in principle, to predict the daylight spectra experienced by idealised (i.e. fixed in position) building occupants. This has found application in studies on the non-visual effects of daylight and the performance of dynamic glazing systems.\textsuperscript{54–56}

However, the enormous diversity in daylight exposure experienced indoors by real occupants is such that it confounds attempts to determine characteristic profiles of actual (photopic) daylight doses, let alone their spectral nature:

\begin{quote}
    The relationship between light and human biology is complex. Light intensity, duration, wavelength and timing, along with the individual history of light exposure and the age of the individual all need to be taken into consideration when characterising these relationships and an appropriate spectral diet.\textsuperscript{57}
\end{quote}

Accordingly, whilst notions such as the ‘spectral diet’ of humans are interesting areas of study in their own right, it seems a remote prospect that these considerations will have an impact on the daylighting design of buildings. In contrast, electric lighting offers the potential for the localised supply and control of illumination (including spectral fine-tuning) and would therefore appear to be a much more likely application area for the findings from photo-biology research. However, as indicated by the quotation above, it may be some time before any consensus is reached in this area regarding how the quantity and quality (i.e. spectrum) of artificial lighting should be controlled.

2.7 Daylighting and the performance gap

All building performance simulation (BPS) is subject to the performance gap (PG) where the disparity between, say, predicted and actual energy use could be large, e.g. a factor of two or more. The reasons for the PG are manifold – there are numerous ways in which a simulation model may deviate from reality. The performance gap with regard to energy use is well documented because, after the building has been occupied for some time, the meters are read and it is possible to compare prediction with reality. Similarly with regard to temperature and (usually) CO\textsubscript{2} levels because these are routinely measured in most modern office/school buildings. Illumination quantities however are, at present, never routinely measured in office/school buildings – only in heritage spaces, art galleries and similar settings for conservation purposes.

To validate CBDM, it would require at least a year’s measured data in a normally occupied classroom or office. Even then, it would be difficult to claim that the simulated operation of the building was identical to that actually occurring, e.g. use of blinds, lights,
etc. In short, how to reliably validate CBDM predictions against measurements in real, occupied spaces is still an unsolved research question – although efforts are underway. This realisation has been used as a reason for recommending against (ever?) using CBDM, and instead relying exclusively on the daylight factor. However, as noted above, the performance gap applies also to any daylight factor-based approach.

Building performance simulation is still carried out on a routine basis to evaluate building design options because, notwithstanding the ultimate disparity with absolute values (which could be large), it is generally believed that BPS will help ‘drive’ the design in the right direction. In other words, whilst the (possibly illusory) absolute target might be the end goal, it is largely the relative outcomes between design options that drive building design. Thus, it makes good sense to use BPS (including CBDM) for design development and refinement.

3. Daylight/sunlight planning

3.1 Guidelines used in the UK

Perhaps the most commonly used guidance document for daylight/sunlight planning in the UK is BR 209 – Site Layout Planning For Daylight And Sunlight: A Guide To Good Practice. From the Introduction to BR 209:

The guide is intended for building designers and their clients, consultants and planning officials. The advice given here is not mandatory and the guide should not be seen as an instrument of planning policy; its aim is to help rather than constrain the designer. Although it gives numerical guidelines, these should be interpreted flexibly since natural lighting is only one of many factors in site layout design.

BR 209 contains a number of rule-of-thumb measures which are conceptually straightforward, although which may need a reasonably accurate 3D model to be applied reliably. In fact, it is arguably the case that application of BR 209 using paper-based plans for even simple scenarios is far more difficult, time-consuming and unreliable than it would be using a 3D model. The same is true for reliable determination of the average daylight factor for all but the very simplest of scenarios. This is counter to claims that have been made by some practitioners that verification of daylight guidelines must necessarily be a ‘paper-based’ procedure.

Sunlight in BR029 is assessed in terms of annual probable sunlight hours (APSH), which is ‘the total number of hours in the year that the sun is expected to shine on unobstructed ground, allowing for average levels of cloudiness for the location in question’. As with other measures in BR 209, APSH was originally conceived as a paper-based method. However, nowadays, this and other measures in BR 209 are determined with much greater ease and reliability using 3D models and computer-based methods.

It is perhaps inevitably the case when guidelines do not contain minimum prescriptive values, that development in urban areas results in an inexorable reduction in available daylight and sunlight for existing properties, and lower expectations for many newer ones. In cities such as New York, the last two decades have seen the construction of super-tall residential towers where much of the premium on these extremely expensive apartments is due to the unobstructed views and plentiful daylight/sunlight – for those few who are literally and financially ‘at the top’.

The following section describes the profound effect that the 1916 Zoning Resolution had on the development of New York City, until it was abandoned in 1961.

3.2 The NYC 1916 zoning resolution

Prior to being dominated by the post-1960s super-tall buildings ‘puncturing’ the sky...
above the city, the skyline of New York had a more undulating appearance typified by the terraced setback of the tall buildings from the first half of the 20th century. The building floor area was progressively reduced with increasing height, and so ‘setback’ from the road whilst also providing opportunity for many (elevated) terraces. The setback was introduced by the 1916 Zoning Resolution with the intention of limiting the loss of view of the sky from the ground. Some of the impetus for this legislation is attributed to the Equitable Building (Figure 5), completed in 1915, it is a ‘40-story extrusion of a whole city block, unrelieved by setbacks and capable of housing 16,000 workers at once’. From 1916 until 1961 (when new zoning rules no longer required any setback), New York acquired its distinctive stepped appearance, evident in this photograph of the Chrysler Building taken in

Figure 5 Equitable Building (photo c. 1915)
1932, Figure 6. Many of those buildings remain, especially in Midtown Manhattan, and are present in the 3D model of the area surrounding the New York Times Building (Figure 3).

The 1916 Zoning Resolution was defined with respect to view from the ground. However, the perimeter spaces of the buildings themselves also benefited from a larger view of the sky than would have been the case if the ground floor plan area had been simply extruded vertically. It is claimed that, notwithstanding the jettisoning of the requirement in 1961, the 1916 Zoning Resolution has had a lasting effect on population density: ‘The 1910 population of Manhattan was 2,331,542, or 164 people per acre. In 2010, the population was 1,585,873, or 109 people per acre.’

3.3 Planning and performance: Different concerns?

The examples from New York City described above illustrate the two extremes which can be thought of as opposite ends of a continuum. For buildings such as the New York Times, the majority of the perimeter glazing has largely unencumbered access to diffuse daylight (i.e. view of the sky) and sunlight (depending on the aspect). Consequently, the potential to make effective use of daylight depends very much on the successful operation of the automated roller-blind shading system. At the other extreme, for those buildings lower down where much of the glazing experiences considerable obstruction, the performance potential for the daylighting of perimeter spaces will be largely predetermined by the built form.
Figure 7. And of course, many urban spaces will fall somewhere between these two extremes.

The research activity in the areas of building performance and urban planning often appear to act independently of each other. Building scientists do carry out (often impressive) multi-factorial studies where, it is claimed, the resultant form is ‘optimised’ to have the lowest possible X, Y and Z (of negative factors such as per capita energy consumption) and the best possible P, Q and R (for desirable factors such as daylighting potential). However, there is usually little discussion how these optimisations might actually be achieved in the real world. This is perhaps understandable since one of the key drivers in academic publishing is novelty, and one of the most straightforward ways of achieving that is by conflation of multiple modelling techniques. The outputs from these are then marshalled by optimisation algorithms and distilled into headline outcomes. Such investigations are now all the more commonplace thanks to the ease afforded by visual scripting interfaces and powerful plugins, e.g. Grasshopper, Ladybug, Honeybee, etc. Whatever the performance gap associated with any individual modelling procedure, the cumulative uncertainty resulting from the conflation of multiple modelling approaches will, of course, be some, much larger aggregate. The cost of building in urban areas is such that design decisions need to be based on certainty, and all risks minimised to the greatest possible extent. These real-world considerations cannot be subordinate to uncertainties resulting from the invariably unknown and often cumulative effects of multiple building modelling performance gaps.

4. Discussion: Squaring the planning–performance circle

A reversion to the 1916 Zoning Resolution for New York now seems unthinkable – enormous constraints would be placed on the volume of buildings permissible on the plots where development opportunities remain. Nevertheless, without some means of applying restraint it seems likely that urban densification will result in buildings with many windows that have little potential to provide useful levels of daylight for the occupants. Key to providing any means of restraint is first having a methodology which can be accepted by all the relevant stakeholders.

For planning purposes, the validity and repeatability of the methodological basis for any daylight/sunlight evaluation are paramount. To have validity, the outcomes should relate meaningfully to the potential performance of actual spaces, e.g. both for the spaces in a proposed development and the determination of the development’s impact on the performance of existing spaces. Additionally, the method must not be subject to the uncertainties of the performance gap – otherwise, it fails the repeatability maxim. If that were to occur, findings would be contested, and decisions based on those results would be challenged in the courts with the various parties employing whichever of the available tools that supports their position. Also, the method should be
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Another key property for any candidate daylight/sunlight planning methodology is that it should not conflict with planning considerations related to other aspects of building performance. Key amongst these are the sunlight-related performance factors of overheating risk and energy generation potential from, say, PV panels. The overheating risk from solar ingress will depend on factors such as window size, aspect, shading and obstruction from surrounding buildings. Similarly, the potential to generate electricity will depend on PV panel size, aspect and neighbouring obstructions. Ideally, even better than avoiding conflict is having a single methodology which is equally applicable to evaluating sunlight potential for amenity, and also for overheating risk and/or PV generation.

To recap, a candidate methodology must be able to gain acceptance from all relevant parties: planning stakeholders and building performance stakeholders alike. Consider the key professional bodies in the UK for building planning/surveying and building performance: The Royal Town Planning Institute (RTPI) and The Royal Institute of Chartered Surveyors (RICS) jointly for planning/surveying, and the Chartered Institution of Building Services Engineers (CIBSE). As far as this author is aware, there is little interaction between CIBSE and either RTPI or RICS for the simple reason that, at present, there is very little overlap between the respective domains of planning/surveying and performance. This is illustrated in Figure 8 – the ‘concept diagram’ for this section. The comfort of occupants has long been a key concern of bodies such as CIBSE, that has extended considerably in the last decade to include health, well-being and productivity. Accordingly, the (circular) icon for performance in the concept diagram (Figure 8) is a composite of the human eye and a building system (a PV panel).

Planning and performance bodies, however, must create some common ground if building energy performance directives are to have any hope of being achieved. The goal of net-zero energy places significant demands on the design of buildings. Windows are always the ‘weak links’ in any facade – both in terms of heat loss and solar heat gain. Either of these can significantly increase operational energy consumption. Excessive solar gain is also a major factor in building overheating, and so can exacerbate the risk of fatalities during periods of extreme heatwave. In addition to reducing operational energy use, the drive towards net-zero buildings prioritises on-site

Figure 8  Squaring the planning–performance circle
renewable energy over off-site (renewable energy). For the majority of buildings, on-site renewable energy is likely to require some component of electricity generation by PV panels. A recent High Court ruling regarding shading of an existing residential PV installation caused by an extension to a neighbour’s property made headlines in the UK: ‘Judge halts house extension after engineer neighbour claimed it would block light to his solar panels in landmark High Court case that rules climate change is a legitimate planning issue’.62

In the ruling given by Justice Lane:

They [the PV panels] make a contribution to the reduction in reliance on non-renewable energy. The fact that, viewed on their own, they do so in a very modest way does not entitle the first defendant to treat the matter as immaterial...63

This ruling has been reported and commented on extensively by Rights of Light practitioners (i.e. the surveyors who will be affiliated to RICS), even though the issue was one of degraded performance of a building component (i.e. typically the domain of CIBSE practitioners) and not a Rights of Light case. As noted in the newspaper headline, this may well prove to be a landmark decision in part because a legal apparatus essentially concerned with building planning was used to make a decision on the basis of degraded building performance. Note, as far as the author is aware, no modelling was carried out to determine the degree of degraded performance.

The necessary bringing together of planning and performance under a common framework (in some manner yet to be determined) creates an opportunity for daylight and sunlight potential that informs on the amenity value and building performance dimensions of each. The method, of course, has to be acceptable to planning bodies, institutions and those who enforce planning law – in other words, it also needs to be readily understood by the legal profession.

4.1 What can be learnt from Rights of Light?

Notwithstanding the significant critique in the last two decades regarding how Waldram determined the ‘grumble point’,22–26 the sky factor method has persisted as the legal basis for Rights of Light for nearly a century. In large part, this is because the precision of the method depends only on the accuracy of the geometrical representation used – Rights of Light practitioners invariably have a background in surveying rather than engineering. The sky factor method is essentially purely geometrical and therefore not subject to any performance gap. For the first half century or so, the sky factor for the Waldram method was calculated using tables and/or drawings which contained 2D projections of necessarily idealised 3D geometry. The first significant change to practice was with the uptake of 3D computer-based modelling tools, beginning in the late 1970s and becoming commonplace in the 1990s. The next was the use of laser range-finder survey techniques to rapidly acquire 3D models of buildings to an unprecedented degree of scale, detail and accuracy. Compared to the original paper-based methods, the geometrical modelling of buildings was now immensely more refined and precise – but the sky factor basis of the assessment remained unchanged. The integrity of 3D representations of buildings is such that there is rarely any dispute over the geometry, and should any arise, it can easily be verified.

4.2 Aperture-based daylight modelling: Linking planning to performance

The following briefly describes a new daylight/sunlight modelling approach which,
The implementation of natural lighting for planning and performance. And so provides a remedy for many of the problems/issues noted above.

Aperture-based daylight modelling (ABDM) is a new modelling schema to evaluate building apertures (or any planar surfaces on the building envelope) based on numerical measures of their ‘connectedness’ to the sun, the sky and the view of the external environment. ABDM is founded on essentially geometrical principles, but nevertheless it can provide meaningful indicators of the daylight/sunlight potential of building apertures (or surfaces, e.g. PV panels). One of the basic principles that distinguishes ABDM from traditional methods used in planning is that it is an area-based approach, i.e. the entire glazed opening (or surface) is considered. Many if not all traditional methods used in planning for, say, sunlight evaluate at a point, e.g. BR 209. A second distinguishing feature (in fact, a consequence of the first) is that all the ABDM evaluations take account of the size of the opening. This point is worth emphasising because, whilst self-evidently a desirable component for the evaluation of sunlight and skylight, opening size is not a factor in the method used in BR 209. A third distinguishing feature (again, a consequence of the first two) is that the results for multiple openings – whatever their size, aspect or orientation – can be combined to give meaningful totals for, say, a particular dwelling.

The evaluation of sunlight, skylight and view at the building aperture presents something of a paradigm shift compared to existing approaches. The sunlight beam index (SBI) was originally conceived as a means to rate a window aperture’s potential to receive sunlight for solar access purposes. SBI is an area measure of the ‘connectedness’ of a building aperture to all of the possible (annually) occurring sun positions for that locale, and for that particular aspect of the aperture including all possible obstructing surfaces – averaged across the aperture. With the area given in square metres and the time period given in hours, the sunlight beam index (SBI) has units of m² hrs. The annual total SBI can be thought of as the time integrated cross-sectional area of sunlight beam that could pass through the aperture in a full year. To correctly account for the shading effect of obstructions – particularly those close to the aperture such as external window reveals, overhangs, balconies, etc. – the SBI is computed at a grid of calculation points across the aperture, typically several hundred to a few thousand.

Similar to the SBI, the aperture skylight index (ASI) is an area measure of the ‘connectedness’ of an aperture to the sky vault in terms of the illumination received from a uniform luminance sky dome calculated across the aperture. To account for the size of the aperture, its ‘connectedness’ with the sky vault is calculated in terms of lumens received at the aperture. Note, in the ABDM schema, the lumen is used in this way as a means of determining ‘connectedness’ between the source (i.e. sky) and receiver (i.e. the aperture) in terms of the illuminance effect of the source on the receiver. In 2019, the concept of the ‘view lumen’ was introduced. This proposed that the measure of an aperture’s ‘connectedness’ to the sky (i.e. the ASI value) is in fact a proxy measure of the potential view (to the sky) from that aperture. Thus, it is a straightforward matter to extend the ASI approach to determine an aperture’s ‘connectedness’ to all three key layers that provide the components of view: ground, foreground (e.g. buildings) and sky. To achieve this, the geometry that comprises each of the view layers is made luminous, and the flux of illumination from each layer (received at the aperture and averaged across it) serves as proxy measures of view (from the aperture) for each of the view layers, Figure 9(a). The figure also includes a
hemispherical fish-eye view out from the centre of the aperture plane – notice the small degree of shading around the periphery due to the external window reveal.

The importance of determining the ABDM metrics across the entire aperture is illustrated in Figure 9(b). The circular images now show hemispherical fish-eye views out from the plane of the aperture for a (coarse) grid of calculation (i.e. view) points. Surrounding the grid of images is superposed an illustration showing the external window reveal. The shading effect of the window reveal varies in degree and character depending on proximity of the image viewpoint to the four sides of the reveal. Whilst this example showed the shading effect of an external window reveal, the ABDM method accounts for almost any degree of external obstructing geometry irrespective of size or complexity providing it can be described in the 3D model.

The latest refinement of ABDM was to apply an airmass factor to the sunlight beam index. In the original SBI formulation, the (normalised) sunlight beam intensity remained constant irrespective of the altitude of the sun. The original SBI therefore possessed an intrinsic drawback: for vertical apertures, low angle sun contributes most strongly to the cross-sectional area of sunlight beam and therefore also the summation of annual total SBI. The solution most in keeping with the ABDM ethos was to include an attenuation factor for SBI based on the airmass. The airmass (strictly, the airmass coefficient) describes the optical thickness of the atmosphere relative to that for the shortest path length (from sea level) directly upwards towards the zenith. For a horizontal view direction (e.g. to the sun at the horizon), the airmass is approximately 40/C² that toward the zenith. Factoring in the airmass gives a new measure of sunlight beam index referred to as SBI-Airmass. This enhancement retains the ‘geometrical purity’ of the ABDM schema. However, SBI-Airmass can now be related directly to irradiation values that would be determined using BPS with a weather file suitable for that particular locale. Thus, SBI-Airmass can serve as a reliable proxy for direct sun irradiation.

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**Figure 9** Aperture connectivity to the view layers (a) and illustration showing how the view of the layers varies across the aperture in the presence of nearby obstructions, i.e. an external window reveal (b) (available in colour in online version)
from weather files which is a measure of the prevailing sunlight conditions for that locale. Multiple dimensions of solar resource can therefore be evaluated at the design stage using the same approach: potential of sunlight for amenity, irradiation potential at the window as an overheating risk, irradiation potential on surfaces for PV generation, etc.

The ABDM schema is outlined in Figure 10.

### 4.3 ABDM and CBDM

ABDM determines measures of the sunlight, skylight and view potential at the window aperture (or surface for PV generation). Whilst it remains yet to be demonstrated, this author is confident that it should be possible to make reasonable extrapolations of, say, daylighting performance inside a space starting from the ABDM measures, in particular SBI-Airmass and the connectivity to the sky. A series of combined CBDM and ABDM evaluations for a range of space types, prevailing climate conditions and varying obstruction scenarios should provide the necessary calibration data. The intention is not to eliminate the need for CBDM, rather it is to provide a reasonable expectation for daylighting potential at the planning stage based only on the ABDM measures.

Similarly, it should be possible to extrapolate the SBI-airmass values at the window apertures to reasonable estimates of solar gain to the connected space, thereby giving an indication of the potential overheating risk from sunlight. Or, equally, the direct solar irradiation on a surface where a PV panel is to be installed.

### 5. Summary

The impetus for what eventually became (in 2019) ABDM was the experience of eight years on EU/CEN panel that delivered EN 17037. This author was primarily occupied with the changes to the performance basis of the standard. However, it was observing the formulation of the planning guidelines part of EN 17037 (largely re-workings of long-established approaches) that led to the conviction that a fundamental rethink was needed. The starting point for ABDM was to put the focus entirely on the building apertures, but at the outside surface of the window. A key part of the rationale was to develop a method which was conceptually very straightforward, but nevertheless capable of delivering worthwhile performance indicators for sunlight, skylight and also view. Another important requirement was the ability to accommodate any degree of real-world geometrical complexity which might be present in a 3D building model – from fine detailing around a window to balconies, overhangs and surrounding buildings. The 3D model for the New York Times project shown in Figure 3 was created in 2004 – any new method had to be able to work with such complexity from the very beginning. The key features of ABDM which make it particularly suited for early design stage evaluation and planning purposes are:

1) A geometrical basis which largely eliminates the potential for error and/or discrepancy in outcomes, i.e. no performance gap.
2) ‘Seamless scalability’ – from the crudest to the most detailed 3D buildings models, the methodological basis of ABDM does not change.

3) ‘Seamless refinement’ – the ABDM metrics can be gradually ‘climatised’ to more realistically represent the prevailing sunlight and skylight conditions derived from localised weather files. This has been described for sunlight. In fact, ABDM can be thought of as a simplified modality of CBDM.

The various components of ABDM are described in a series of papers from 2015 to 2020. A paper giving the latest, complete formulation of ABDM is in preparation.

The multiple goals of achieving sustainable development in the built environment whilst providing interior spaces that sustain and promote health and well-being, and doing so within the cost-constrained realities faced by developers, necessarily results in competing interests. One of the essential functions of planning is to reconcile the competing interests with the least possible compromise for all relevant stakeholders, not least the future occupants of those buildings. The increasing importance given to both the internal environment (e.g. occupant well-being) and the overall building performance (e.g. net zero) will, sooner or later, result in the realisation that current practice must somehow be upgraded to account for these factors at the earliest stages of design/planning. Aperture-based daylight modelling has, this author believes, the necessary properties to serve as the basis for the evaluation method to fulfil that need.

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