Aperture-Based Daylight Modelling: Introducing the 'View Lumen'

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Abstract

This paper presents a new way to determine measures of view at the building aperture. It introduces the concept of the view lumen – this is the illumination effect received at the building aperture from a visible external entity (e.g. ground, sky, obstruction, etc.) which is made self-luminous for this purpose. The paper describes the fundamental principle behind the view lumen, and gives some preliminary illustrations of the technique to show its potential. The examples employ the British Standard framework to define categories of view. That is, three layers named upper, middle and lower comprising, respectively, sky, natural or man-made objects (e.g. buildings) and ground. The proposal is an extension of the recently introduced sunlight beam index.

Introduction

The guidelines and recommendations currently used to evaluate daylight and daylight related quantities for planning purposes are invariably simplistic in conception, having changed little since they were first devised a half-century or more ago. Techniques such as climate-based daylight modelling (CBDM) are generally preferred by practitioners to evaluate building designs (Mardaljevic (2006)). However they are currently deemed too complex for their use to be made mandatory for regulatory purposes, though there is one notable example where evaluation of school building designs using CBDM is compulsory (Mardaljevic (2015)). This paper proposes a novel framework for the evaluation of daylight and view which has all the features necessary to form the basis of a regulatory method for planning purposes. The basis of the approach is to evaluate meaningful measures of sunlight, skylight and view for individual or groups of building apertures, i.e. windows. Importantly, and unlike many of the existing approaches, the new method accounts for the window size. Although this first implementation uses *Radiance*, the calculation is fundamentally geometric and therefore suited for implementation as, say, a BIM plugin. The outcome is largely immune to accidental blunders or deliberate game playing providing the geometry is correct – an essential consideration for any method that could form the basis of, say, a future EU/CEN standard.

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 (Mardaljevic and Roy (2016)). SBI is an area measure of the 'connectedness' of a building aperture to all of the possible occurring sun positions for that locale and for that particular aspect of the aperture including all possible obstructing surfaces – averaged across the aperture. Similarly, 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 – averaged across the aperture (Mardaljevic (2017)). This paper introduces the concept of the 'view lumen' as a measure of the aperture's 'connectedness' to the three key layers that provide the components of view: ground, foreground (e.g. buildings) and sky. In effect, 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 for each of the view layers.

View 'layers'

The following is from British Standard BS 8206-2 Lighting for buildings – Code of practice for daylighting (British Standards Institute (2008)):

"Daylighting gives to a building a unique variety and interest. An interior which looks gloomy, or which does not have a view to the outside when this could reasonably be expected, will be considered unsatisfactory by its users."

'*'Most unrestricted views have three 'layers', as follows:*

1. *upper (distant), being the sky and its boundary with the natural or man-made scene;*
2. *middle, being the natural or man-made objects themselves;*

3. lower (close), being the nearby ground.

Views which incorporate all three 'layers' are the most completely satisfying."

The formulation of view as comprising three 'layers' provides the framework for the proposal here that the lumen can be used as proxy for view. The lumen is the SI unit of luminous flux (symbol ϕ, units lm). The SI unit of illuminance lux (symbol E units lx) is defined in terms of lumens per unit area, i.e. $1\,\text{lx}{=}1\,\text{lm}\,\text{m}^{-2}$.

The principle behind using the lumen as a proxy for view at the building aperture is simple: the illuminance effect (at the aperture) of a self-luminous object is taken to be a measure of the potential view of that object from the aperture. This is in fact a direct extension of a recently proposed concept called the aperture skylight index which, to provide the necessary context, is described below.

The aperture skylight index

The aperture skylight index (ASI) was conceived as a measure of the 'connectedness' of an aperture to the sky vault in terms of illumination received from a uniform luminance sky (Mardaljevic (2017)). This measure was chosen in preference to, say, the solid angle of sky visible at the aperture for a number of reasons:

1. Illuminance received at the aperture relates more directly to the illumination potential of the aperture than solid angle because it already includes the cosine weighting of the visible sky.
2. The determination of solid angle has to be made at a point, say, the middle of the aperture, whereas the illuminance can be determined across the entire aperture.
3. The use of illuminance determined across the aperture allows for accurate evaluation of arbitrarily complex shading structures, e.g. brise-soleil, mashrabiya, etc.

The CIE standard overcast sky formulation was not used because it is in fact an "extreme" type of overcast sky that occurs in reality much less often than its commonplace usage for daylight evaluations might suggest (Enarun and Littlefair (1995)). Furthermore, the ASI is intended to be a measure of connectedness between the aperture and the sky irrespective of any particular sky luminance pattern. In that regard, it is perhaps more in keeping with at least part of the original rationale for the daylight factor, i.e. to provide a rating irrespective of the actually occurring conditions (Mardaljevic and Christoffersen (2017)). The daylight factor approach may be said, with hindsight, to have 'jettisoned' that founding rationale when the uniform sky was replaced with the CIE standard overcast sky formulation (Mardaljevic (2013)).

The sky is defined as a hemisphere of uniform luminance. The luminance L assigned to the uniform sky is $2000/\pi\,\text{cd}\,\text{m}^2$. This normalises the sky to deliver 2000 lx of illuminance on the horizontal. Or equivalently, a $1\,\text{m}^2$ unobstructed horizontal aperture receives 2000 lm of illumination from the sky, Figure 1. A vertical aperture 'sees' half as much sky as a horizontal one. Thus the aperture skylight index for a $1\,\text{m}^2$ unobstructed vertical aperture is 1000 lm.

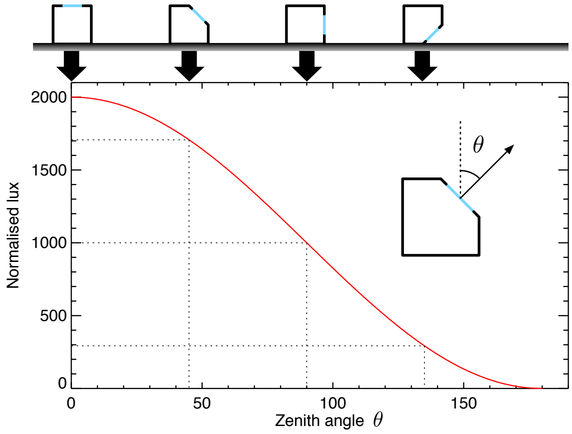

Figure 1: Normalised lux from a sky of luminance $2000/\pi$ cd m^2 as a function of zenith angle θ

The lumen as a proxy for view

Keeping with the convention devised for the aperture skylight index, but extending now the concept to include view, every square metre of aperture has the potential to receive 2000 lumens of 'view' from the self-luminous entities that comprise the external scene. Thus the measure of view of the sky is numerically equal to the aforementioned aperture skylight index. As noted in the previous section, a horizontal $1\,\text{m}^2$ aperture in a thin roof (e.g. a skylight) 'sees' only the sky and so has an aperture skylight index of 2000 lm. In the new schema, the aperture has 2000 lm of view of the sky. And, of course, no view whatsoever of anything else. A vertical $1\,\text{m}^2$ aperture in a thin wall receives 1000 lm of view of the sky and 1000 lm of view of the ground (in the absence of any obstructions). The middle 'layer' in the British Standard document is that comprising 'natural or man-made objects', hereafter referred to as 'obstructions' for brevity since they can obstruct a view of either or both of the sky and ground 'layers'. This is illustrated in Figure 2 where the three layers of sky, obstructions and ground are coloured, respectively, red, green and blue.

As noted in the Introduction, the illuminance received at the building aperture from each of the layers is calculated using the *Radiance* lighting simulation system (Ward Larson et al. (1998)). The luminous entities are described in the simulation as follows. The sky and non-local ground are described as source solid angles, i.e. effectively at infinity. This creates a continuous luminous envelope without any gaps (Figure 2). Nearby ground surfaces are assigned

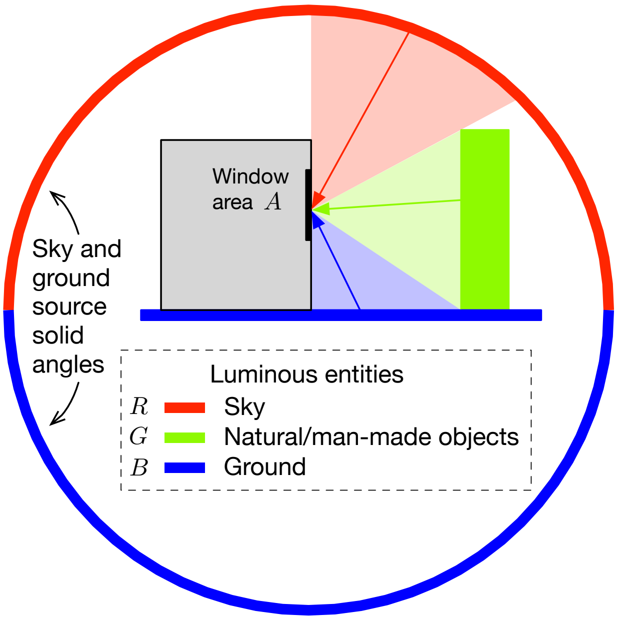

Figure 2: Specification of the luminous environment to calculate the view lumen

the same luminance as the (distant) source solid angle ground. Obstructions which comprise the middle latey are similarly assigned an equivalent luminance. The *Radiance* system has three channels which are generally used to compute each ray's contribution to RGB spectral irradiance, i.e. the primaries commonly used in computer graphics to generate colour images. Note, strictly speaking, luminous entities in the *Radiance* system are described in terms of their spectral radiance. Thereafter, photometric quantities (typically, illuminance and/or luminance) are derived from the spectral radiance/irradiance values. However, for simplicity, the luminous entities in the *Radiance* scene(s) are described here in terms of their (derived) photometric values rather than the actual radiometric quantities specified in the input files.

That the British Standard refers to three layers of view which is also the number of spectral channels used by *Radiance* is, of course, merely a coincidence. Albeit a useful one since the illuminance contribution from three (luminous) view layers can be determined in a single run by setting each respective view layer to have a red, green or blue radiance value. This also helps with regard to intelligibility of the scene content since the layers are readily identified by their colour, as will be demonstrated in the examples that follow.

Scene 1: Illuminance and view at a point

Scene 1 description

This example demonstrates the basic principle for using illumination as a proxy for view by considering the illumination effect of a unit square polygon (e.g. 'obstruction') at various distances and for three view vectors. A graphic of the scene is shown in Figure 3. The obstruction is positioned centrally above the XY plane and aligned along the y-axis. There are five calculation points distributed along the positive y-axis with distance from the obstruction/origin y_p ranging from 0.2 to 5. The view vector defines the orientation of the (virtual) surface for the calculation of illuminance, i.e. it is the surface normal for the (virtual) receiving surface. The three view vectors are: directed towards the obstruction; directed 45° away from the obstruction; and, directed 90° away from the obstruction (Figure 3).

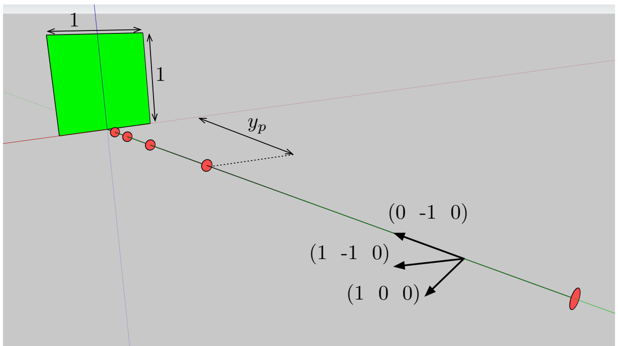

Figure 3: 3D graphic of scene 1 showing obstruction and the five calculation points.

Hemispherical and angular fish-eye renderings of the scene from the viewpoint y_p=0.2 and directed along vector $(0 \quad -1 \quad 0)$ are shown in Figure 4. Note, the hemispherical fisheye view more closely relates to the illuminance received at the point than the angular view.

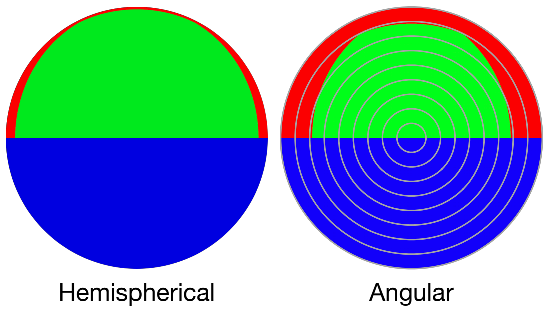

Figure 4: Hemispherical and angular (normal) views of obstruction at y_p=0.2.

Scene 1 results

The hemispherical fisheye view of the obstruction and the illuminance effect produced by it at all 15 combinations of five viewpoints and three view vectors are given in Figure 5. The illuminance at the point produced by the (green) obstruction is superposed over the (blue) ground. For all cases, the total illuminance from all three view layers is 2000 lux:

$$2000 = E_{sky} + E_{obs} + E_{gnd} \tag{1}$$

The ground comprises half the view in every case, thus the illuminance effect of the ground E_{gnd} is 1000 lux for all the cases shown in Figure 5. Thus the illuminance effect of the sky E_{sky} (not shown in the figure) is simply:

$$E_{sky} = 1000 - E_{obs} \qquad (2)$$

Figure 5 also shows the solid angle of the obstruction ω_{obs} from the point y_p for each of the five distances. This illustration clearly shows how the illuminance effect of the obstruction varies with distance and view direction. At the viewpoint closest to the obstruction (y_p=0.2), the illuminance effect diminishes from 921 lux to 310 lux (i.e. by a factor of ∼3) as the viewpoint shifts from normal to orthogonal. At y_p=1 the change in view direction results in the illuminance diminishing from 360 lux to 42 lux: a ∼9 drop. At y_p=2 the same change in view direction results in a drop of ∼16.

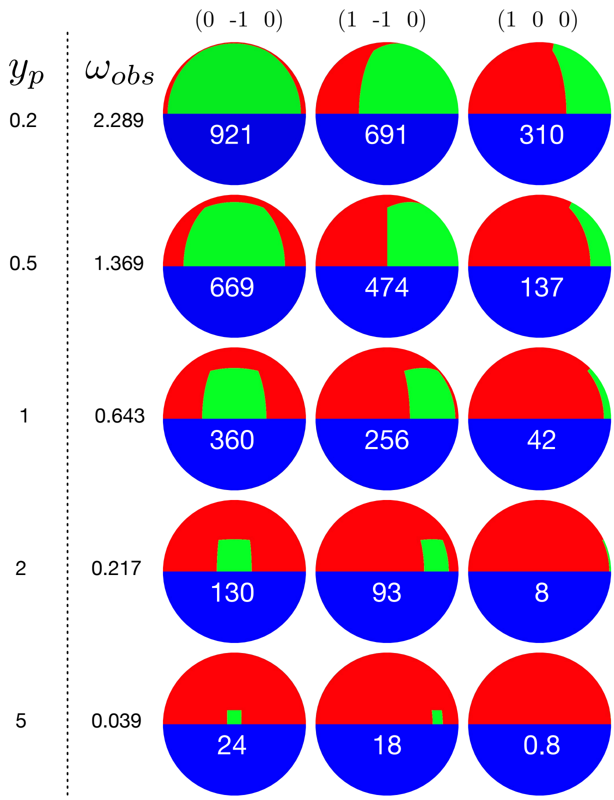

Figure 5: Illuminance received from the obstruction at all 15 combinations of five viewpoints and three view vectors

The same data presented graphically better illustrates the relation between distance, view direction and the illuminance effect of the obstruction. Readily apparent in Figure 6, the fall-off in solid angle closely follows the overall trends in the diminution of illuminance with increasing distance from the obstruction. However, of course, the solid angle subtended by the obstruction at any particular distance is the same irrespective of view direction, whereas the illuminance effect varies strongly with view direction. It would appear largely self-evident from this simple illustration that the illumination effect from the layers of view certainly has some potential to serve as a basis for the quantification of view. This is further extended in the example below where, rather than illuminance at a point, it is lumens arriving at an aperture that form the the measure of view.

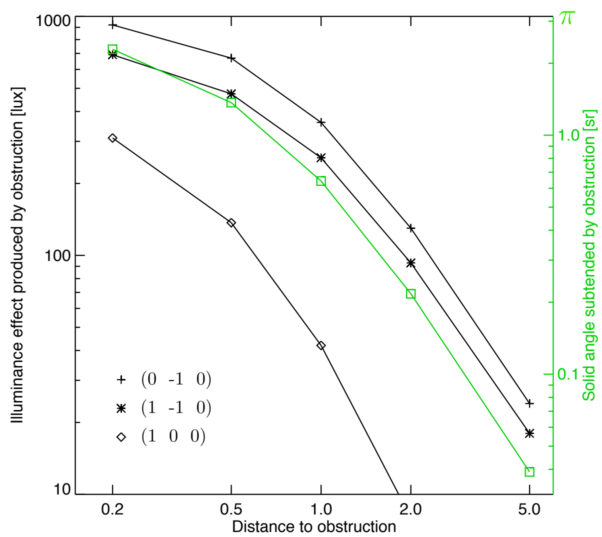

Figure 6: Illuminance effect and solid angle as a function of distance.

Scene 2: View lumens at an aperture

Scene 2 description

This scene comprises a hypothetical room with a 1 m^2 window aperture set in a 0.3 m deep reveal – deliberately chosen to be large to demonstrate the view shading effect of intrinsic structural elements, Figure 7. A measure of the view of each of the three layers from the aperture is taken to be equivalent to the lumens arriving at the aperture from each of the three layers in turn. The first two cases (A and B) consider the view layers of sky and ground only. To illustrate the view shading effect of the reveal, the first case (A) considers the aperture without the reveal; and the next case (B) with the reveal. Three 'natural or man-made' obstructions are evaluated in turn: a sloped object (C); a set of six vertical strips (D); and, a small square obstruction (E), Figure 7.

For comparison, the view lumens calculated across the aperture are compared with the view lumens calculated at a single point at the middle of the aperture – numerically this is equal to the illuminance calculated at the point multiplied by the area (i.e. 1 m^2).

Scene 2 results

Prior to the five A to E cases, the first result presented here is an illustration of the difference between an area calculation of lumens and a point esti-

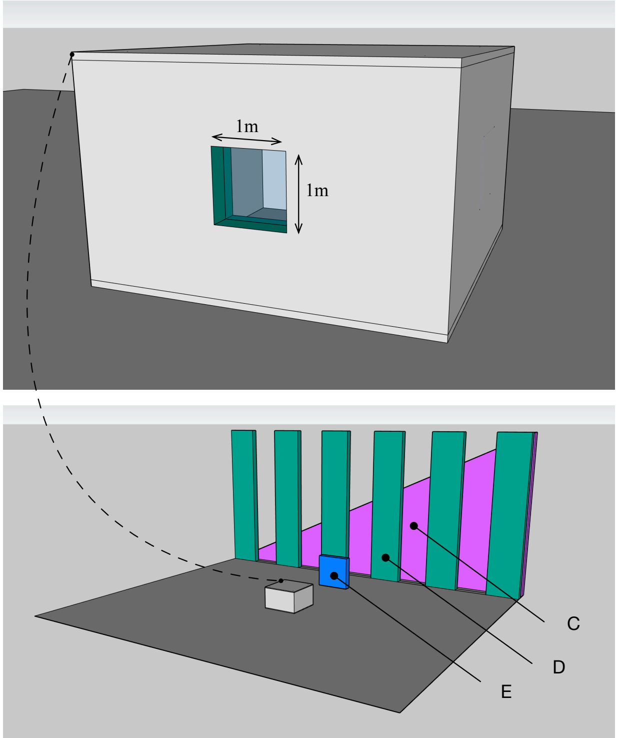

Figure 7: 3D graphic of scene 2.

mate when intrinsic shading structures such a window reveal are present. The illuminance across a $1\,m^2$ aperture set in a 0.3 m reveal is presented in Figure 8. Note, for this illustration there is no attempt to make a distinction between the three view layers. Recall that all the luminous entities in the scene (apart from intrinsic structural elements) have a luminance of $2000/\pi\,cd\,m^2$, and so will produce an illuminance of 2000 lux in the absence of any shading from intrinsic structural elements. Thus, without a reveal, the illuminance across the aperture would be a uniform 2000 lux. With the reveal, however, the illuminance across the aperture ranges from a minimum of 471 in the corners to a maximum of 1556 lux in the middle. The mean illuminance across the aperture $\overline{E}$ was 1159 lux (Figure 8). The total lumens ϕ received at the aperture area A is simply:

$$\phi = \overline{E}A \tag{3}$$

Thus the $1\,m^2$ aperture received 1159 of the maximum possible 2000 view lumens. The 'lost' lumens are those caused by the shading of the reveal, i.e. a view loss due to self-shading by intrinsic structural elements. Consider now the degree to which the middle point estimate of lumens received (i.e. 1556 lm) exceeds the actual value calculated across the aperture (i.e. 1159 lm).

Since each square metre of aperture has the potential to receive 2000 lm of view, the view lumens lost due to shading by intrinsic structural elements (reveals, overhangs, balconies, etc.) is, in the general case for an aperture area A, simply:

$$\phi_{lost} = 2000A - (\phi_{sky} + \phi_{obs} + \phi_{gnd}) \tag{4}$$

Thus, 841 lm of view were lost due to the deep reveal for the example shown in Figure 8.

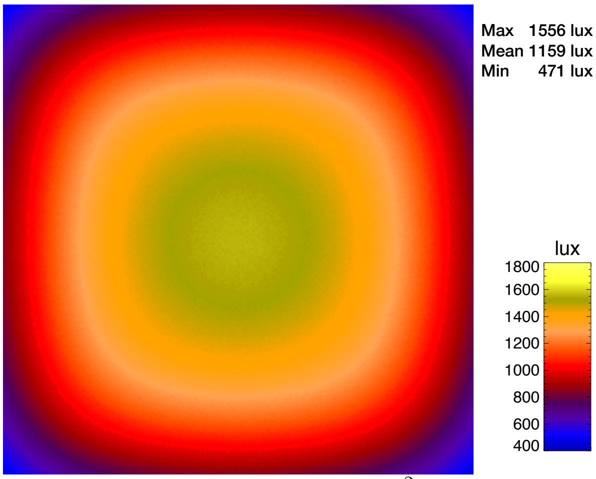

Figure 8: Illuminance across a $1m^2$ aperture set in a 0.3 m reveal

Moving on now to the point estimate and aperture values of the view lumens for the five A to E cases, the results are summarised in Figure 9. For each case, the view lumens from each of the three layers are shown for the point estimate and the aperture calculation. The rendering shows the simulated view of each case from the centre of the aperture.

Case A: For both the point estimate and aperture calculation the results are identical – both predict a 1000 lm of view of the sky and a 1000 lm of view of the ground. To be expected since, without a reveal, the view of the scene does not vary across the aperture.

Case B: Now the shading effect of the reveal markedly diminishes the view lumens from both the sky and the ground, however the reduction for the aperture (1000 to 580 lm) is much greater than that for the point (1000 to 774 lm). The view lumens calculated using the single point totalled 1548 lm, whereas those calculated across the aperture totalled 1160 lm.

Cases C to E: For these remaining cases there are three view layers. In each case, the point calculation significantly overestimates the view lumens arriving at the aperture compared to the aperture calculation. The degree to which this occurs depends on the visual extent of the obstruction from the aperture. For cases C and D the point calculation overestimates the view lumens of the obstruction significantly – by approximately a quarter and a third respectively. However, for case E, where the obstruction is centrally placed and subtends a small angle, the overestimation is negligible, i.e. 136 view lumens compared to 130 for the aperture calculation.

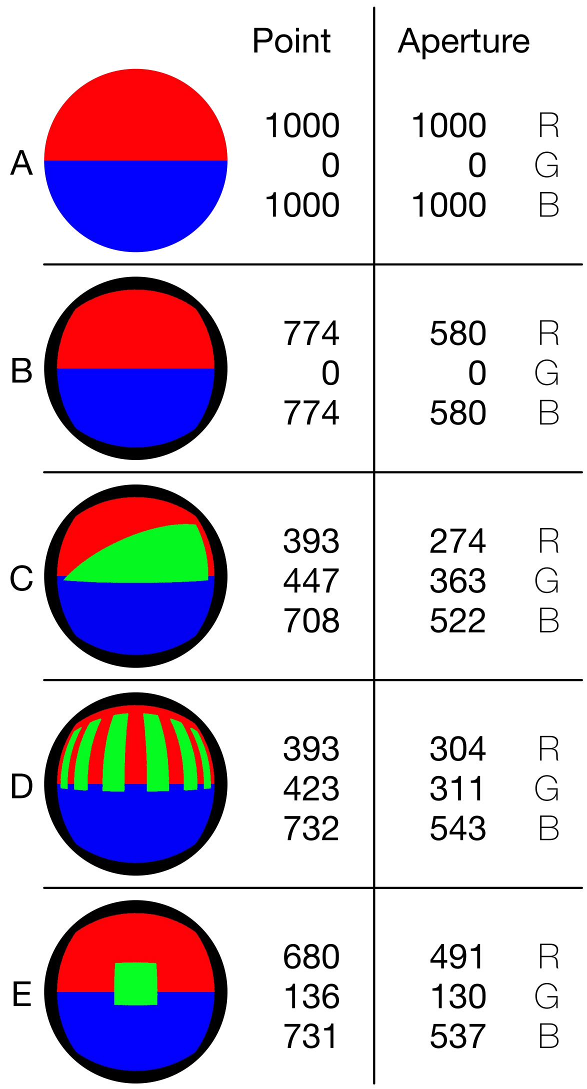

Figure 9: Lumens received from sky, obstruction and ground – point and aperture calculation

The sunlight beam index

To complete the picture presented here of, what is tentatively called, 'aperture-based daylight modelling', a brief recap of the sunlight beam index is given in this section. As noted in the Introduction, the sunlight beam index is a measure of an aperture's 'connectedness' to all of the annually occurring possible sun positions where sunlight can be incident on the aperture (Mardaljevic and Roy (2016)). A single, unambiguous measure of sunlight beam potential forms the basis of the sunlight beam index (SBI). The annual SBI is the cumulative measure of the cross-sectional area of sunbeam that can pass through a window aperture over the period of a full year. It accounts for all the possible above horizon sun positions and is determined on an hourly or sub-hourly basis. SBI therefore has a temporal dimension and can be decomposed into a series of shorter aggregate time periods, e.g. 12 monthly totals, 24 monthly am and pm totals, etc.

With the area given in square metres and the time period given in hours (or more typically, a fraction of an hour), the sunlight beam index (SBI) has units of m^2 hrs. This formulation makes good sense for a number reasons:

- It is consistent with fundamental illumination physics (e.g. the cosine law of illuminance as a proxy for reduced area of cross-sectional beam).
- The penetration depth of the sun's rays into the space will be reduced with increasing angle of incidence.
- Large incidence angle sun illumination on the window will have a proportionate (i.e. small) contribution in any evaluation without requiring any recourse for arbitrary cut-off conditions, e.g. 'dead angles', etc.
- The glazed area is properly accounted for.
- Shading – whatever its origin – is properly accounted for.

Any meaningful evaluation must account for the entire year of possible sun positions to capture all of the potential occurrences of sun and and, importantly, shading also.

An example temporal map for an unobstructed 1 m^2 south-facing vertical aperture for London, UK is shown in Figure 10. Note, the scale shows a maximum of 0.25 m^2 because the SBI is determined for 15 minute increments (for this 1 m^2 aperture). As expected, the highest SBI values occur around noon in winter when the angle between the sun position and the aperture surface normal is the smallest. The annual SBI is 1927 m^2 hrs, i.e. this is the total cross-sectional area of sunlight beam that could pass through the aperture in a year for that orientation/location (under continuous clear sky conditions).

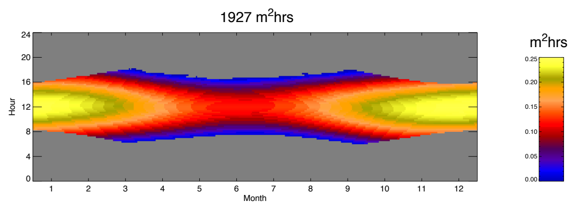

Figure 10: Sunlight beam index temporal map for a 1 m^2 south-facing aperture in London, UK.

If required, the total SBI for a dwelling or building can be obtained by summing all SBIs for the relevant windows or window groups. Thus it becomes possible to characterise the sunlight beam index for an entire building (e.g. dwelling) with a *single* SBI value (Mardaljevic and Roy (2016)). The same could easily be achieved to calculate the combined view potential for any or all of the apertures in a dwelling, apartment or building using the view lumen method described here.

Discussion

The rationale for the sunlight beam index was to have an approach that could form a common basis across, say, all EU/CEN countries for the evaluation of sunlight at almost any level of geometrical complexity. In fact, the impetus for it was the direct result of serving on an EU/CEN panel for a number of years and witnessing at first hand the intractability of either improving existing methodologies (all different in one way or another) by incremental means or fashioning from them a synthesis which could work effectively across all relevant building scales and for all nations. Since it appeared that the existing methodologies were not capable of any incremental improvement that could lead to a viable synthesis, a fundamental rethinking of the basis for the evaluation of the sunlight potential in buildings was needed. This resulted in the sunlight beam index. Shortly afterwards, as a complement to SBI, the aperture skylight index was devised as a measure of the 'connectedness' (i.e. skylighting potential) of the aperture.

That rationale has been further extended here to the consideration of measures of view determined at the window aperture. The aperture skylight index has effectively been subsumed within the view lumen framework since the methodology and the numerical measure is identical.

Outside – Inside

The connectedness of a building aperture to all of the possibly occurring sun positions together with measures of the three layers of view (including the intrinsic shading of view) are, it is proposed, potentially very useful indicators of building performance to have at the early stages of building facade design. The sunlight beam index gives a measure of the potential for sunlight provision, and so could serve as a proxy for various related aspects of building performance e.g. glare, overheating, etc. Similarly, the measure of view/connectedness to the sky (ϕ_{sky}) is an indicator of the skylighting potential of the aperture. How these measures relate to actual performance indicators, say, sunlight fluxes and skylight lumens computed using CBDM is yet to be determined – this is ongoing work.

How the measures of view lumens relate to traditional notions of the assessment of view in spaces (e.g. those in the recently published CEN standard FprEN 17037) presents a rather more challenging task. Views from inside, of course, depend on a number of factors – some related to the building design, others essentially arbitrary (e.g. selected assessment positions) and/or subjective without perhaps a general consensus regarding key determinants of outcome (e.g. width of the desired view). The proposal presented in this paper cannot settle any of those issues. However it does perhaps offer another way to approach them.

Rather than prescribing guidelines for view as it is presently done (i.e. from inside to outside), another approach could be to give recommendations for key geometric properties of the internal space based on the provision of so many view lumens for each of the layers (determined at the aperture). Importantly, the sky layer provides a measure of the skylighting potential of the aperture – a key consideration. Some prescription would need to be given regarding the position of the aperture(s) for their potential to offer view, e.g. something like: 'a given percentage of the area of the aperture(s) must fall within a given height range above the floor'. Other prescriptions could relate to the volume of the space together with, say, the aspect ratio of the floor plan, etc. Another consideration perhaps is the placement of the aperture within the wall thickness. For view in particular, it could be argued that the aperture used for calculation should be a virtual surface coplanar with the inner wall surface, i.e. taking account also of the internal wall reveal depth. These are merely speculations to provoke discussion.

Rights to light

Any new obstruction could have a detrimental effect (i.e. injury) on the daylight provision to the surrounding buildings depending on the particulars of the proposed design/context. Attempts to systematise the assessment of daylight injury date back to at least the 1800s (Kerr (1865)). Daylight injury can be measured in terms of the reduced view of the sky or the diminished illumination from it. Or, it could be judged in terms of the potential reduction in direct sun insolation, either for particular times of the day/year or the number of annual probable sunlight hours (Littlefair (2011)). The method used may depend on local custom/practice or a legal requirement. In the UK, the possible infringement of "daylight adequacy" to an existing space by a proposed building is sometimes determined using the "rights to light" schema (Harris (2007)). The century-old "rights to light" schema, originally devised by Waldram, has been critiqued in a number of papers, e.g. see Chynoweth (2009) and Defoe and Frame (2007).

Given the simplicity of the aperture metrics, it should be possible to determine if there is any relation between a user's perception of the asset value of a window and its 'connectedness' to the sky and/or sun as indicated by the view layers metrics and the sunlight beam index. Such a study would be best carried out on geometrically similar/identical apartments that have different levels of view of obstructions, the sky and the possible sun positions. Thus an aperture-based assessment of daylight injury could be a more straightforward replacement for the Waldram method than say, full-blown climate-based daylight modelling (Mardaljevic et al. (2015), Ross and Quy (2018)).

Building performance pedagogy

The author believes that the aperture-based approach described here could help to encourage a more 'mindful' approach to full-blown daylight simulation than appears to be the case today. The proliferation of easy-to-use climate-based daylight modelling tools, in particular those that allow for routine parametric analysis, has resulted in something of a *'simulate first, think later'* mindset. Such tools often proclaim that they are "user centric" and that the generation of voluminous parametric results somehow "empowers the user". The reality often appears to be somewhat different: the easy-to-generate reams of simulation output are just as likely to overwhelm rather than empower the user. Whilst parametric analysis clearly has its uses, the case is made here that simulation novices (and not just novices) might better appreciate the basic principles of daylighting and solar shading from first understanding the performance of the building space at the envelope level (i.e. the apertures) before venturing to predict daylight metrics for the inside of the space.

Looking ahead

The idea presented here is perhaps something of a departure from what one normally expects in building science nowadays, i.e. invariably an addition, extension, enhancement, etc. to a well-established technique. As such, it may require something of a pause for thought to properly consider the possibilities that aperture-based daylight modelling offers. As noted, the impetus for it was direct experience on EU/CEN panels resulting in, for this author, the realisation that (radical?) new ideas were needed in order to rethink the basis of building standards/guidelines, certainly for application at the planning level.

Acknowledgment

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