PLEA 2017 EDINBURGH

Design to Thrive

Envelope first / Inside later: Aperture Sunlight and Skylight Indices

John Mardaljevic[1] and Nicolas Roy[2]

[1]School of Civil and Building Engineering, Loughborough University,
Loughborough, UK email: j.mardaljevic@lboro.ac.uk;
[2]VELUX A/S, Ådalsvej 99, DK-2970, Hørsholm, Denmark

Abstract: This paper describes a back-to-basics rethinking for quantifying the sunlight and skylight potential of building apertures. The recently formulated sunlight beam index (SBI) approach has been conflated with a complementary metric called the aperture skylight index (ASI). 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. In a complementary fashion, the aperture skylight index is a measure of an aperture's 'connectedness' to the hemispherical sky vault. In the absence of any localised shading/obstructions, the sunlight beam index depends on the location, orientation (i.e. azimuth angle), aspect (i.e. zenith angle) and size of the aperture. The SBI is the cumulative measure of the cross-sectional area of sunbeam that can pass through a window aperture. In contrast, the ASI depends only on the size and aspect of the aperture in addition to shading/obstructions – it has no dimensions of time and it is not dependent on the azimuth orientation of the aperture relative to the hemisphere of sky. Obstruction of the aperture's 'connectedness' to either the sky or the entirety of possible sun positions can de due to: features integral to the facade (e.g. external window reveal); shading devices; or, any external structures. The effect of obstructions, whatever their origin or complexity, is automatically accounted for in the computation of the indices – the only requirement is that they are included in the 3D model of the scene. The approach provides designers and product specifiers with an intuitively simple "aperture rating system" to evaluate and compare the in-situ performance of building apertures in combination with any shading system. Application of the rating system is demonstrated for a residential dwelling.

Keywords: Windows, shading, sunlight, skylight, planning.

Introduction

The sunlight beam index (SBI) was originally conceived as a means to rate a window aperture's potential to receive sunlight for planning and solar access purposes (Mardaljevic and Roy, 2016). This paper describes a complimentary extension to the sunlight beam index. The extension was formulated to be a measure of the 'connectedness' of the aperture to the sky vault. In other words, an indicator of the aperture's potential to supply diffuse skylight to the interior. In rule-of-thumb evaluations, the amount of sky visible at the workplane is taken to be a governing factor for general daylight illumination. A similar basis is now applied to the window aperture, and the measure is called the aperture skylight index (ASI). Together, the two indices form the basis of a *contextual* sunlight and skylight performance rating system for building apertures. The rating system accounts for the location, orientation and aspect of an aperture in addition to any integrated shading device and/or any external obstructions.

The Sunlight Beam Index

A single, unambiguous measure of sunlight beam potential forms the basis of the sunlight beam index. Since the sunlight beam index is a relatively new concept, the theoretical basis for it is given below (Mardaljevic and Roy, 2016).

Theoretical Basis for SBI

Consider a glazed aperture of area A_g. When this area of glazing is illuminated by the sun at normal incidence for a period of time Δt, the sunlight beam index $S_{\Delta t}$ for that duration of time is equal to the product of the illuminated area A_i and the time period. Thus the sunlight beam index (or SBI) is a measure of the cross-sectional area and duration of direct sun beam that enters a space. For the case of normal incidence with no obstructions (i.e. $A_i = A_g$):

$$S_{\Delta t} = A_g \Delta t \tag{1}$$

However, when the angle of incidence θ is greater than 0°, the sunlight beam index is reduced by the cosine of the angle because the cross-sectional area of the transmitted beam is reduced by that amount, Figure 1. Thus the illuminance at the window plane serves as a proxy for the reduced cross-sectional area of the transmitted beam:

$$S_{\Delta t} = A_g \cos\theta \Delta t \tag{2}$$

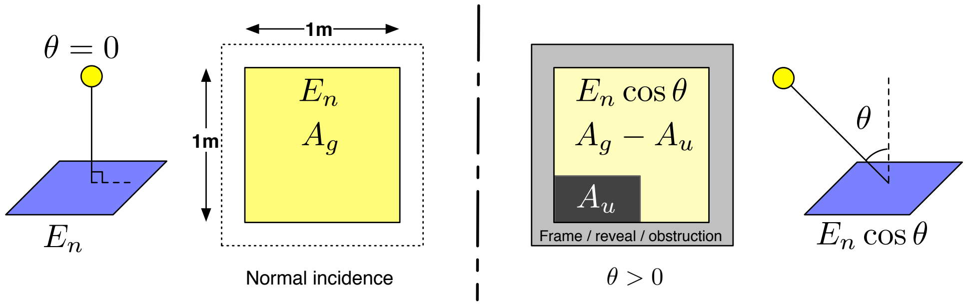


Figure 1: Angle and shading effects in the evaluation of the SBI

Most window glass will be fixed in a frame that stands proud 'above' the surface of the glass, i.e. the glass is, in effect, recessed within the frame. Thus, any direct sun illumination on the glass at non-normal incidence will result in the frame and/or reveal casting a shadow onto the glass. In other words, the illuminated area of glass will be less than the total area of the glazed aperture, i.e. $A_i < A_g$. The area of glass in shade (or 'umbra') is A_u:

$$A_g = A_i + A_u \tag{3}$$

Shading of direct sun can also result from any other structure, nearby (e.g. balcony) or more distant (e.g. obstructing tall building). Combining the angle and obstruction effects, the generalised sunlight beam index equation is:

$$S_{\Delta t} = A_i \cos\theta \Delta t = (A_g - A_u) \cos\theta \Delta t \tag{4}$$

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. How this is done is described in the following section.

Annual Sunlight Beam Index

The total sunlight beam index S_{tot} for any glazed aperture – or group of glazed apertures – is the sum of all the individual sunlight beam indices for the entire year where the sun altitude γ_s is greater than zero:

$$S_{tot} = \sum_{\gamma_s > 0} (A_i \cos\theta \Delta t) \tag{5}$$

Additionally, the individual values of $S_{\Delta t}$ for the entire year can be used populate a 2D matrix that can be visualised as a temporal map **T** which has dimensions 24×365 for hourly data (i.e. $\Delta t = 1$ hr). For a time-step of 15 minutes, the temporal map array has dimensions 96×365. An example temporal map for an unobstructed 1 m^2 south-facing vertical aperture for London, UK is shown in Figure 2. 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.

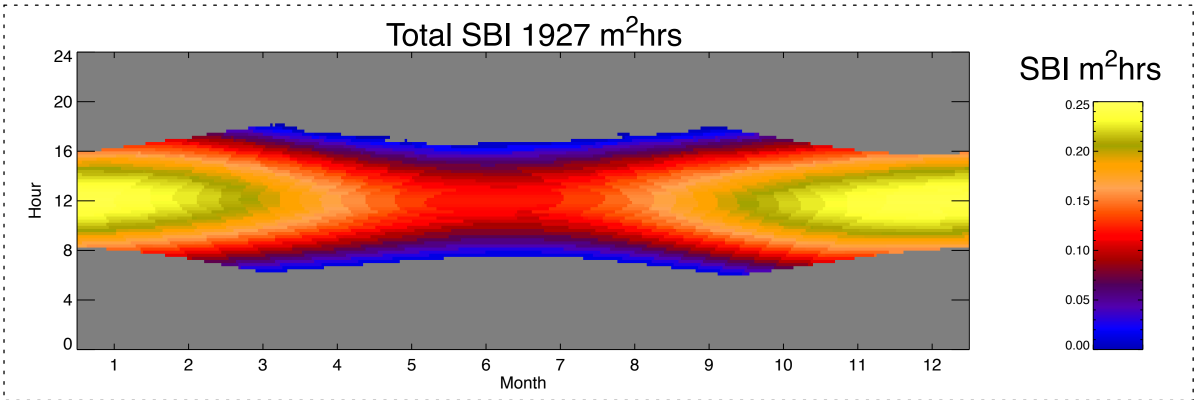


Figure 2: Temporal map for an unobstructed 1 m^2 south-facing vertical aperture for London, UK

For a space with n multi-aspect windows (or window groups) labelled a, b, etc. the total SBI for the space is simply the sum of the individual SBIs:

$$S_{space} = S_a + S_b + \ldots + S_n \tag{6}$$

Similarly, the temporal map for the space is the sum of the individual temporal map arrays:

$$\mathbf{T}_{space} = \mathbf{T}_a + \mathbf{T}_b + \ldots + \mathbf{T}_n \tag{7}$$

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.

The Aperture Skylight Index

As noted in the Introduction, the aperture skylight index (ASI) is 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:

(i) 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.
(ii) 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.
(iii) 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).

Direct comparison of skylight and sunlight potential is confounding for a number of reasons. However, the two can be assessed side-by-side, and comparative evaluations made readily intelligible provided that suitable normalisations are applied for the computation of the indices. The sunlight beam index has a natural normalisation as described in its original formulation – it has units of m^2 hrs. For a 1 m^2 unobstructed vertical aperture, the annual SBI for London (UK) varies between 204 m^2 hrs (facing north) and 1927 m^2 hrs (facing south). There is no compelling reason to adjust these numbers with any subsequent normalisation of SBI. Whilst there is no direct equivalence between sunlight and skylight potential, for the purpose of making comparison and general interpretive simplicity, it is beneficial to have the skylight potential normalised so that the skylight index has a similar magnitude to the range in SBI (for any given size of window aperture). Thus, the skylight index is normalised so that a 1 m^2 vertical aperture has a value of 1000. The actual units are lm, or m^2 lux to make a parallel with the SBI units of m^2 hrs. The sky is defined as a hemisphere of uniform luminance. The luminance L assigned to the uniform sky is 2000/π cd m^2. This normalises the sky so that a 1 m^2 unobstructed vertical aperture receives 1000 lm (or 1000 m^2 lux) of illumination from the sky. A horizontal aperture 'sees' twice as much sky as a vertical one. Thus the skylight index for a 1 m^2 unobstructed horizontal aperture is 2000 lm. The relation between the incident illuminance E_θ and the angle θ between the (sky) zenith and the aperture is given by:

$$E_\theta = 1000 \cos\theta + 1000 \quad (8)$$

The relation is shown plotted in Figure 3 with graphic annotations showing the glazing aspect (i.e. zenith angle) for E_θ = 0° to 135° in steps of 45°.

Example Application of ASI and SBI

The residential dwelling shown in Figure 4 is used to demonstrate the application of the new approach to a real world example. This dwelling, referred to as the 'Row House' model , is surrounded by a sparse arrangement of neighbouring houses, and the effect of horizon obstructed by houses in the distance is accounted for by an 'enclosing' cylinder (Figure 4). The 'Row House' has 16 window groups labelled according to the 10 distinct internal spaces for which the windows provide illumination. For example, 'glaz01' is the label for the three window panes that comprise the single group for an upstairs bedroom. Whereas the three window groups 'glaz07a', 'glaz07b' and 'glaz07c' comprise all the windows for the sunroom (Figure 4).

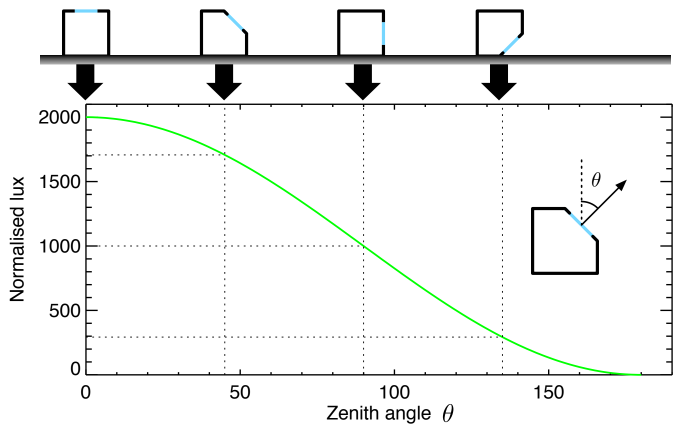


Figure 3: Normalised lux as a function of zenith angle

For the SBI component of the example shown here, the location of the 'Row House' model was set to London (UK) and the results for three orientations of the house are presented. For the ASI component, the location and orientation of the dwelling have, of course, no bearing on the outcome.

The results are given in Table 1. The first column gives the label for the window group and the second gives the area of glass for that group. The third column gives the aperture skylight index for the window group. Whilst the remaining three columns give, respectively, the total annual sunlight beam index for the window group for the orientations 000, 090 and 180 (London, UK). The total ASI and SBIs are given for the entire dwelling and also for the just the three 'glaz07' groups that comprise the sunroom (additionally labelled *). The last row of the table shows graphics indicating north (compass icon) and the orientation of the dwelling.

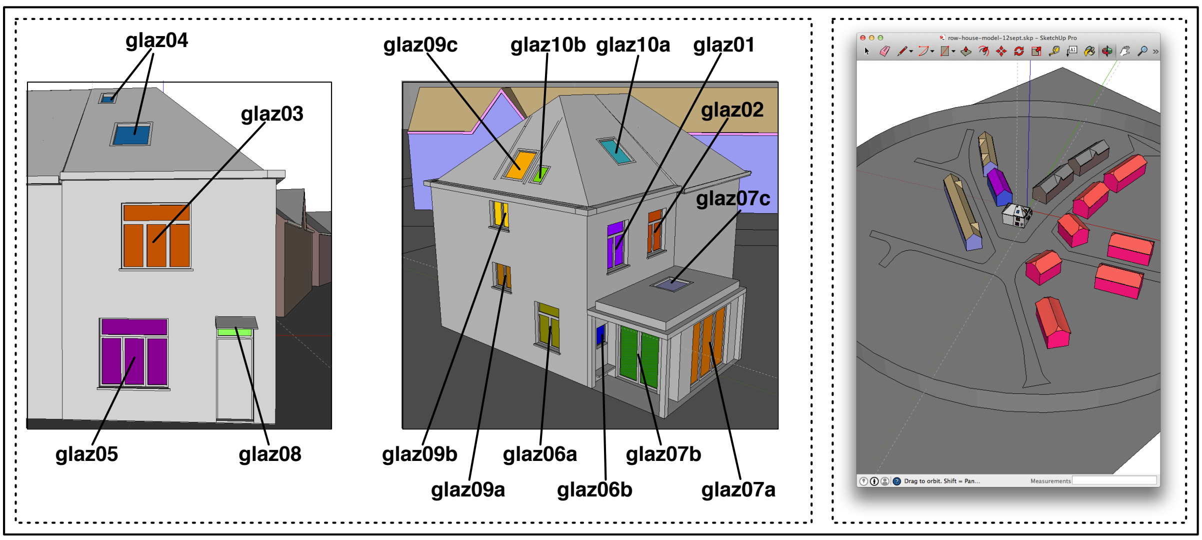
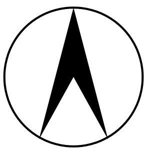
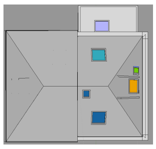
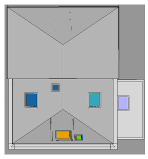
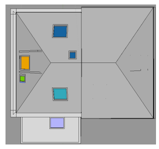


Figure 4: Row house model and site context

Looking first at the total value of the indices for the entire dwelling, the ASI equals 17,739 normalised sky lumens whilst the SBI has values of 16,130, 24,694 and 20,800 m^2 hrs for orientations of 000, 090 and 180 respectively (London, UK). The SBI values show how sensitive the overall sunlight potential of the dwelling is to the orientation. The total SBI for the contri-

Table 1: Aperture skylight (ASI) and sunlight beam (SBI) indices for the all the glazing groups in the residential house model. Location used for SBI is London (UK) and values for three house orientations are given.

Label	Area (m^2)	ASI	SBI (000)	SBI (090)	SBI (180)
glaz01	1.54	945	23	1332	2051
glaz02	1.54	946	24	1359	2024
glaz03	2.33	1543	3130	2213	108
glaz04	1.46	2156	3215	2149	579
glaz05	2.48	1498	3005	2150	47
glaz06a	1.54	821	1099	1749	947
glaz06b	0.48	46	0	87	102
glaz07a*	5.19	2804	33	3542	5926
glaz07b*	3.46	1078	1500	2210	1622
glaz07c*	1.05	1203	268	973	1454
glaz08	0.34	19	25	39	1
glaz09a	0.72	369	506	817	483
glaz09b	0.72	387	595	855	570
glaz09c	1.22	1712	1791	2767	1775
glaz10a	1.21	1827	517	1845	2716
glaz10b	0.24	385	399	607	395
Total	25.52	17739	16130	24694	20800
*Sunroom only	9.7	5085	1801	6725	9002
					

bution from sunroom shows a different pattern: it is greatest for the orientation 180 where it contributes nearly half of the overall dwelling sunlighting potential. The ASI and SBI values for any particular window group can be read from the table, allowing for a precision evaluation of the skylighting and sunlighting potential for any of the distinct spaces in the dwelling.

At a more strategic level, the temporal dimension of SBI can be applied to evaluate overall sunlighting for the dwelling across the year as a function of, say, building orientation. Rather than show the temporal maps at their full 15 minute resolution (e.g. Figure 2), the maps have been processed to show monthly am and pm totals. Temporal maps for eight building orientations are shown in Figure 5. As before, the location for the dwelling is London, UK. Each temporal map is annotated with the overall annual total. Presented in this way, the SBI maps readily reveal the am/pm and seasonal sunlighting potential of the dwelling for any particular orientation.

The highest annual SBI of 24,694 m^2 hrs is for orientation 090. Conspicuous in the temporal map are the three high monthly am totals for May, June and July. Now consider orientation 135, here the map shows a similar overall annual total, but much more evenly spread throughout the year without any am or pm monthly total exceeding 1320 m^2 hrs, and the smallest monthly total never less than 513 m^2 hrs. For orientation 225 the annual total of 17,938 m^2 hrs is markedly less than that for orientation 135, however the May, June, July and August pm totals are high: ranging from 1492 to 1626 m^2 hrs. High monthly pm totals during summer could be an indication of overheating risk. For any given dwelling design, a site planner may wish to avoid building orientations that exacerbate overheating risk due to solar gain.

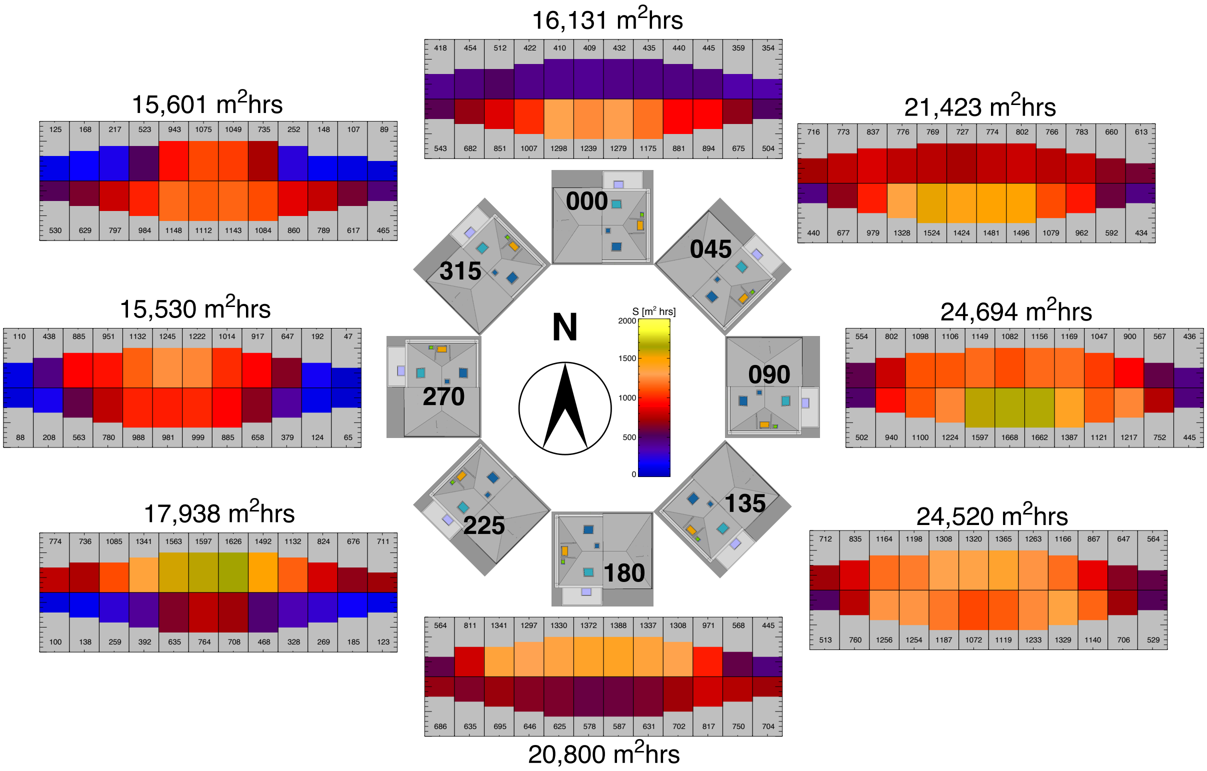


Figure 5: Total am/pm SBI per month for all eight orientations (London, UK).

Discussion

The aperture and sunlight beam indices approach offers a means to readily estimate the sky-lighting and sunlighting potential of building apertures. The approach has much in common with simple 'rule of thumb' methods, however it is much more precise and, importantly, entirely scaleable: it can accommodate almost any level of real-world geometrical complexity. Although the *Radiance* lighting simulation system was used as the 'engine' in the implementation described here (Ward Larson et al., 1998), lighting simulation *per se* is not required to compute SBI since the method depends only on a line-of-sight calculation, the modelling of inter-reflection and/or the transmission/scattering effects of light are not needed. Thus, SBI could in principle be computed by any 3D CAD/BIM tool that can determine if there is line-of-site visibility between two points: one in the building model, the other at a sun position on the sky vault. Furthermore, the accuracy of the results that one gets are entirely depended on the faithfulness of the model description: good 3D geometry ensures accurate values for the indices. Perhaps ASI/SBI values should be determined at the earliest stages of design by a plugin application to any widely used BIM tool such as REVIT.

The skylight and sunlight aperture rating system provides both designers and product specifiers with intuitively simple means for both evaluating and comparing the in-situ performance of building apertures in combination with any shading system, e.g. brise-soleil. The rating system has several qualities that make it well suited for the teaching of skylighting and solar shading principles. Indeed, the authors hope that the rating system could help to encourage a more 'mindful' approach to full-blown daylight simulation than appears to be the case today since the proliferation of easy-to-use climate-based daylight modelling (CBDM) tools, in particular those that allow for routine parametric analysis, has resulted in something of a *'simulate* *first, think later'* mindset.

The ASI-SBI approach has the potential to find application is many areas in addition to teaching, e.g. first-stage performance evaluation of the building envelope for skylighting and sunlighting potential; product specification for any integrated shading system; site planning of residential developments; and, perhaps also as a basis for guidelines governing urban planning. It is hoped that many if not all of these possibilities will be investigated in the near future.

Funding and Acknowledgements

The original idea for the sunlight beam index is based on a study commissioned by the VELUX Corporation. Professor Mardaljevic acknowledges the support of Loughborough University.

References

Enarun, D. and Littlefair, P. (1995), Luminance models for overcast skies: Assessment using measured data, *Lighting Research and Technology* 27(1), 53–58.

Mardaljevic, J. (2013), Rethinking daylighting and compliance, *Journal of Sustainable Engineering Design* 1(3), 2–9.

Mardaljevic, J. (2017), Aperture Sunlight and Skylight Indices: A Rating System for Windows and Shading Devices, *CIBSE Technical Symposium, Loughborough, UK* 5-6 April.

Mardaljevic, J. and Christoffersen, J. (2017), 'Climate connectivity' in the daylight factor basis of building standards, *Building and Environment* 113, 200–209.

Mardaljevic, J. and Roy, N. (2016), The sunlight beam index, *Lighting Research and Technology* 48(1), 55–69.

Ward Larson, G., Shakespeare, R., Mardaljevic, J., Ehrlich, C., Phillips, E. and Apian-Bennewitz, P. (1998), *Rendering with Radiance: The Art and Science of Lighting Visualization*, San Francisco: Morgan Kaufmann.