Examples of Climate-Based Daylight Modelling

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Abstract

The daylight factor persists as the dominant evaluation metric because of its simplicity rather than its capacity to describe reality. The daylight factor is insensitive to both the prevailing local climate and building orientation. The drive towards sustainable, low-energy buildings places increasing emphasis on detailed performance evaluation at the early design stage. Recent advances in lighting simulation techniques have demonstrated that reliable predictions founded on hourly climatic data are attainable. The first part of this paper describes the application of climate-based daylight modelling to recent projects in New York and St. Petersburg. A climate-based daylighting metric to replace daylight factors is described. The second part of the paper is a discussion on the origins and practice of "traditional" daylight modelling.

Introduction

Climate-based daylight modelling is the prediction of various radiant or luminous quantities (e.g. irradiance, illuminance, radiance and luminance) using sun and sky conditions that are derived from standard meteorological datasets. Whilst it hardly needs remarking that daylight is inherently climate-dependent and time-varying, the accepted evaluation method, called the daylight factor, makes no account of this everyday reality. The principles of climate-based daylight modelling have been described in various publications since the first reports around the turn of the millennium [Mardaljevic 2000] [Reinhart 2000]. But it is fair to say that acceptance has been slow amongst significant sections of the daylighting community, both practitioners and researchers. Some of the likely reasons for this are discussed in the second part of the paper.

The first reports on climate-based daylight modelling tended to describe its possible uses rather than its application to real-world examples, as was to be expected for a new technique. Five years on, the value of climate-based daylight modelling is starting to gain acceptance through its successful application to live projects and its role as an “engine” to help formulate new daylighting metrics.

This paper describes the practical application of climate-based modelling to two fairly typical design evaluation problems that would normally have been “solved” using standard techniques. The third example is theoretical case study to demonstrate application of a new climate-based daylighting metric called “useful daylight illuminance”.

Solar access study: the Arts Students League, New York, USA

Founded in 1875, the Arts Students League (ASL) boasts an alumni list that is a veritable Who's Who in American art, from Winslow Homer and Georgia O'Keeffe to Mark Rothko, Jackson Pollock and Louise Nevelson. The ASL artists, teachers and students, both past and present, have all placed great value in the daylight afforded by the skylights. A development is proposed for the through lot immediately west of the ASL building, Figure 1. The proposed tower has the potential to reduce the daylighting of the two studios on the top floor of the ASL. The challenges for the evaluation of potential injury were as follows:

- Determine some meaningful measure of the reduction in daylight levels caused by the proposed building.
- Quantify the sensitivity of the injury to various design alternatives.
- Determine the limits of mitigation that can be reasonably expected.

The standard evaluation methods that were initially offered to the clients by a US-based practitioner were either inappropriate or could not address fully their concerns. For example, the skylights are North facing and receive hardly any direct sun, so a shadow pattern study is fairly pointless. Even if that had not been the case, the shadow pattern method offers only qualitative indicators of likely impact. The daylight factor approach was rejected because the client was aware how the character of illumination in the ASL studios depends on the various sky conditions, including the potential for reflected sunlight from nearby buildings.

The solution offered to the client was an assessment of the daylight injury in terms of realistic measures of illumination determined using New York climate data. Total annual illumination is a measure of all the visible daylight energy incident on a surface over a period of a full year. Standard climate datasets contain hourly values for various irradiation and illumination quantities. From these it is possible to derive hourly-varying sky and sun conditions for use in lighting simulations. Equally, it is possible to synthesize cumulative luminance “maps” for arbitrary periods (e.g. annual, monthly, etc.) that contain the aggregated luminance effect of all the unique hourly sky and the sun values. Separate luminance maps for the annual cumulative sun and the annual cumulative sky were synthesized from the standard climate TMY2 dataset for New York City (WBAN# 94728).

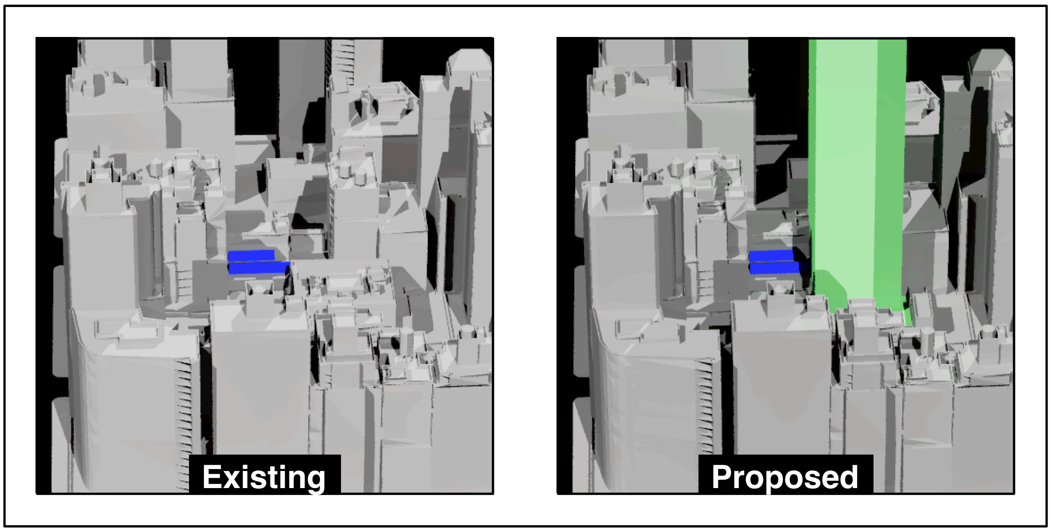

Figure 1. Rendering of ASL building (skylights in blue) for existing and proposed scenarios (proposed tower in green).

These cumulative luminance maps were used to determine the sky and sun components of total annual illumination (TAIL) incident on the skylights of the ASL. The simulations were carried out for the existing arrangement of buildings (as shown in Figure 1) and with the proposed tower in place.[1] Simulations for the proposed tower were carried out with the tower reflectivity set first to zero and then to 50%. The zero reflectance case determines the diminution of TAIL from the tower acting purely as an obstruction. For the 50% reflectance case, the tower acts both as an obstruction and a reflector of light (sky and sun). A reflectance of 50% is the highest that can be expected for an exposed vertical facade. The effect of intermediate reflectivity values for the proposed tower can be determined from a simple interpolation of the results for the zero and 50% cases. A sample of the results are presented in Figure 2, the location of the skylights is outlined in the left-most image. In addition to the mean TAIL for each skylight marked on the images, the inset value shows the area-weighted mean in TAIL for both skylights.

The area-weighted mean TAILs were 36,600 klux hours for the existing scenario, 23,500 klux hours with a tower of zero reflectance and 30,000 klux for a tower with

[1] Additional simulations not reported here were carried out to determine the effect of rotating the proposed tower by 90°.

50% reflectance. For the client, the differences in the predicted levels of total annual illumination gave a realistic evaluation of the daylight injury from the proposed tower. Furthermore it was remarked that total annual illumination was a far more meaningful measure of daylight availability than 'abstract' quantities such as the daylight factor.

Figure 2. Illumination maps for the ASL skylights. Annotation shows total annual illuminance across the skylights. Inset value shows area-weighted mean. The view is a "close-up" of the skylights identified in blue in Figure 1.

Daylight for museums: the Hermitage, St. Petersburg, Russia

Climate-based lighting simulation was used to predict the distribution of mean illuminance for each month, and the total annual exposure to daylight in rooms of The General Staff Building (part of the Hermitage Museum), St. Petersburg, Russia. Hourly climate data for St. Petersburg was processed to faithfully represent local time including summer daylight savings. Twelve cumulative monthly climate files were created using only the period of visiting hours which is 10h00 to 18h00. Separate climate files were created for the sun and the sky components of illumination. Monthly cumulative luminance maps for the sun and sky conditions were derived from each of the monthly climate files.

Simulations showing a hemispherical view of the inside of the room were generated for each of the 24 luminance maps, i.e. 12 sky and 12 sun. The simulations for the sun component were carried out with inter-reflection both enabled and disabled. In this way it was possible to determine the amount of the total illumination that was due to direct sun only. Markers in a mask image were used to identify those pixels in the illuminance images that were coincident with specified points on the wall. Graphics of the 3D model are given in Figure 3.

The total annual exposure is simply the sum of the 24 monthly sun and sky illuminance images. The mean illuminance for each month was the sum of the cumulative sun and sky illuminances for that month divided by the number of visiting hours for that month. The results for two points in a West facing room are given in Figure 3 below the graphics of the 3D model. The approximate positions of the marker points on the wall are indicated by the 'link lines' between the plots and the room section. The mean illuminance is given by the total height of the bar in the plots. The magnitude of any direct sun component is indicated by magenta shading to the lower part of the bar. The inset in each gives the total annual exposure in units of klux hours.

Daylight is often the preferred source of illumination for museums and art galleries. However, the annual exposure to illumination is a key consideration for the preservation of the majority of art objects. For example, the Scottish Museums Council recommend a maximum exposure of 450,000 lux hours per year for "moderately sensitive items", and 100,000 lux hours per year for "very sensitive items". Climate-based modelling can supply good estimates of exposure and illumination at any stage of the design process. The cumulative monthly approach described here offers a compact form of presentation and is ideally suited to the scheduling of, say, the seasonal deployment of shading or blinds to minimise exposure to direct sun.

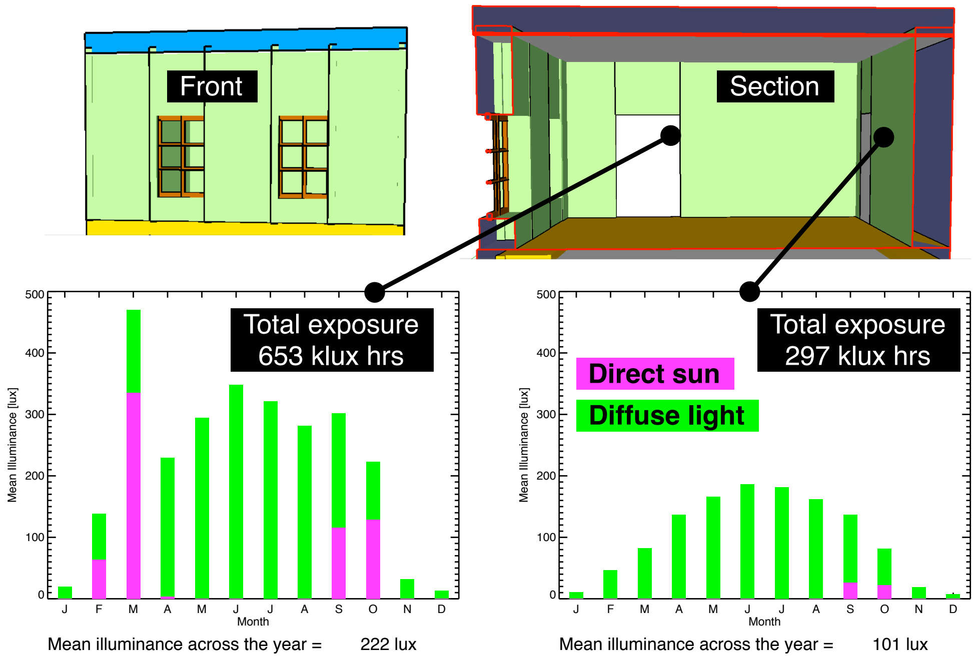

Figure 3. Mean illuminance for each month and total annual exposure for two points in the General Staff Building, St. Petersburg (West facing, 10h00 to 18h00).

Useful daylight illuminance: a replacement for daylight factors

The previous two examples simulated the illuminance effect of annual and monthly cumulative skies derived from hourly climate data. The finest level of temporal detail offered by a climate-based lighting simulation is one that predicts time-varying daylight illumination at the time-step of the climate data. For most climate files this will be hourly and result in the generation of ~4000 illuminance values (i.e. number of daylight hours) for every calculation point. Useful daylight illuminance (or UDI) is a new scheme to determine meaningful measures of daylight provision from the voluminous mass of illuminance data.

Put simply, achieved UDI is defined as the annual occurrence of illuminances across the work plane that are within a range considered "useful" by occupants. The range considered "useful" is based on a survey of reports of occupant preferences and behaviour in daylit offices with user operated shading devices. Daylight illuminances in the range 100 to 500 lux are considered effective either as the sole source of illumination or in conjunction with artificial lighting. Daylight illuminances in the range 500 to 2000 lux are often perceived either as desirable or at least tolerable. UDI is the defined as the annual occurrence of daylight illuminances that are between 100 and 2000 lux.

UDI is informative and disarmingly simple

The UDI scheme is applied by determining at each calculation point the occurrence of daylight illuminances that:

- Are within the range defined as useful (i.e. 100 lux to 2000 lux).
- Fall short of the useful range (i.e. less than 100 lux).
- Exceed the useful range (i.e. greater than 2000 lux).

Thus, only three metrics are needed to provide a compact representation of the hourly-varying daylight illuminances for an entire year at each of the calculation points.[2] The 2000 lux upper limit was based on the reported behaviour of occupants in daylit buildings. It was around the 2000 lux mark that blinds were drawn and/or dissatisfaction was noted. Further, it seems plausible that the occurrence of UDI exceeded (i.e. >2000 lux) is likely to be related to the building's propensity for excessive solar gain. In other words, this simple scheme can provide useful information on the intrinsic shading effectiveness of the building as well as on the daylight.

Application of the UDI scheme is demonstrated using predictions of daylight illumination for a building with a central light-well, Figure 4. The building has standard clear double glazing and the Basecase version is totally unshaded. Variant 1 has a shading overhang on the East, South and West facades. Variant 2 additionally has a lantern with shaded top over the light well. Internal floor, wall and ceiling reflectances were set to typical values. These details however are unimportant for the purpose of demonstrating the UDI scheme.

Hourly daylight illuminances at work plane height across the ground floor were predicted for the Basecase and both shading variants using the rigorously validated daylight coefficient technique [Mardaljevic 2000]. London (UK) climate data was used to generate the hourly-varying sky and sun conditions. The results are presented in Figure 5. The top row of images show the percentage of the working year[3] for which daylight illuminances were in the range 100-2000 lux (i.e. UDI achieved). The plots below the images show the achieved UDI along the East-West transect (dotted line in the images). As well as UDI achieved, the line plots show UDI exceeded and UDI fell-short. For the unshaded Basecase design, the line plots show that the low occurrence of UDI achieved for the perimeter was due to the high occurrence of UDI exceeded, i.e. of illuminances >2000 lux which are likely to cause discomfort. The same is true for area below the unshaded light-well (Basecase and Variant 1).

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[2] Following discussions (by teleconference) with participants of the Seattle Daylighting Forum meeting (21-22 July, 2005) it was suggested that the scheme could be enhanced with just a small addition in complexity by partitioning the UDI range into 100-500 lux and 500-2000 lux. These have been provisionally called UDI-supplementary and UDI-autonomous for the lower and upper ranges respectively. That is, supplementary light *might* be needed for daylight illuminances in lower range, whereas daylight alone is sufficient when it is in the higher range.

[3] A shortened working day was used which gave few hours of afternoon darkness in the Winter.

The UDI plots (achieved, exceeded and fell-short) readily disclose the effect of adding shading to the Basecase building. The UDI schema preserves much of the interpretive simplicity of the familiar daylight factor approach.

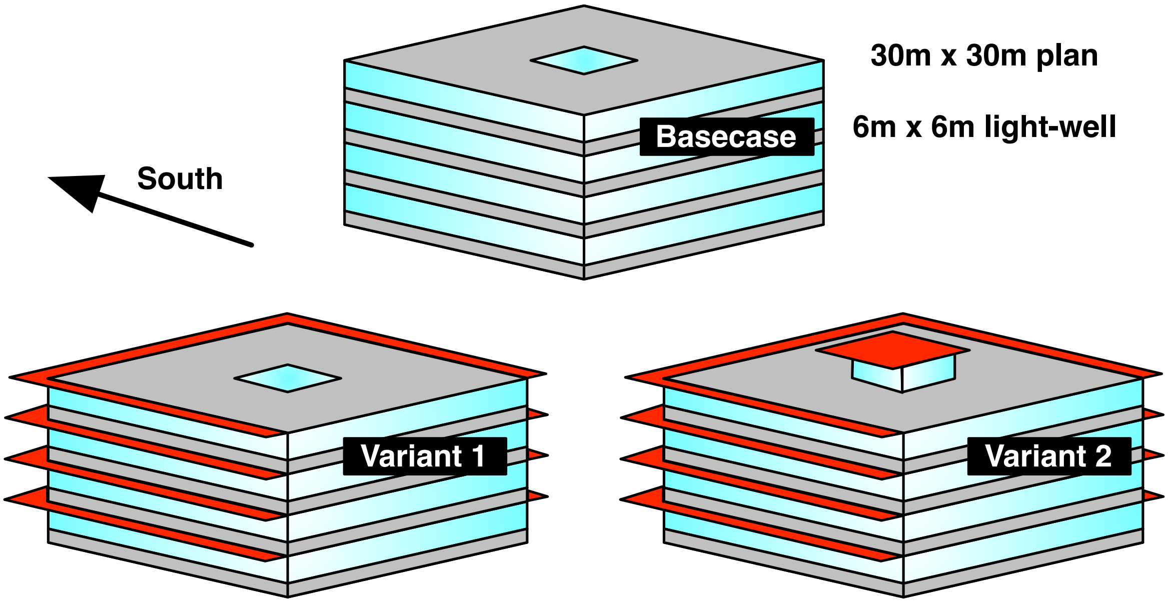

Figure 4. Light-well building for useful daylight illuminance example. Basecase - no shading; Variant 1 - 1m shading overhang on E, S & W facades; Variant 2 - addition of lantern and shading over light-well.

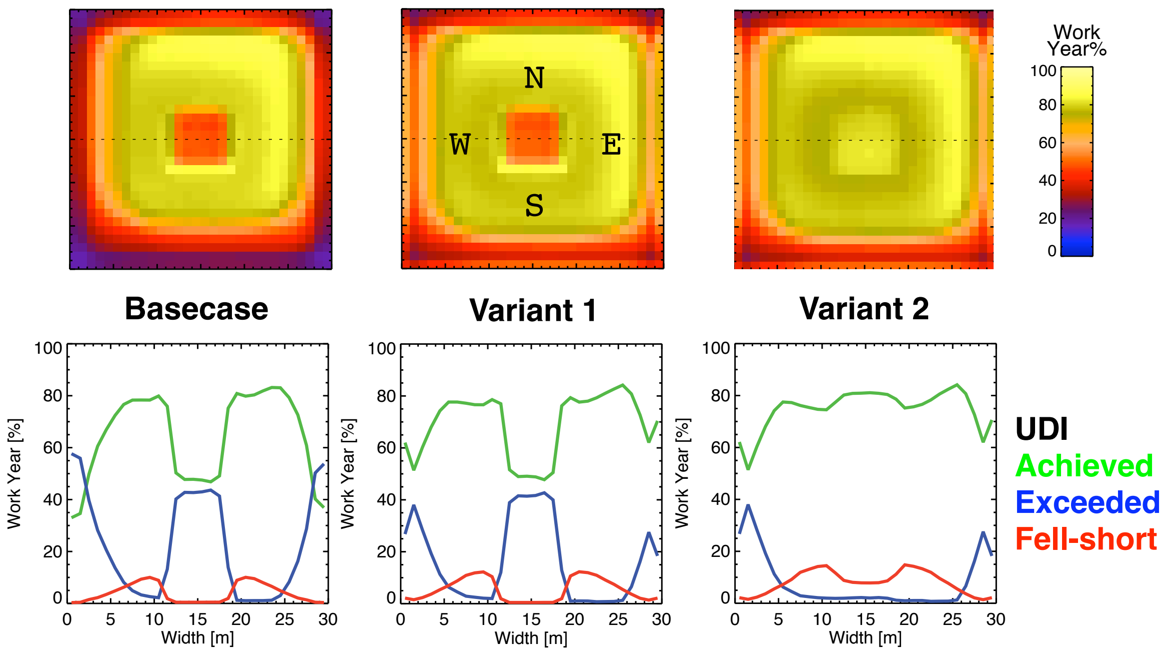

Figure 5. Images of UDI achieved (top row) and below plots of UDI achieved, exceeded and fell-short along the East-West transect. Predictions are the ground floor of the building.

Coda

Daylight is invariably promoted as a 'good thing', and the literature contains abundant articles in support of the evidently worthy intent to provide 'good daylight' for our buildings. The exploitation of daylight, commonly referred to as 'daylighting', is recognized as an effective means to reduce the artificial lighting requirements of non-domestic buildings [Crisp 1988]. In practice however, daylight is a greatly under-exploited natural resource. Significant amongst the various reasons for this is the inability of the standard predictive methods to account for realistic conditions. Nearly twenty years after Crisp's report daylighting remains as under-exploited as ever. Perhaps a good part of the reason for this is that the promoters of good daylighting encounter difficulties when they are asked to clarify just how worthwhile daylight really is. It is generally the case that low-energy buildings incur greater costs at the design stage than the standard building types. For successful low-energy buildings, the additional design costs are often recovered from the reduced capital spend on HVAC and the lower running costs. In terms of cooling and natural ventilation, low-energy passive design principles for non-domestic buildings are fairly well established, as are the design-cost implications and the likely long-term cost benefits.

Good daylighting seems rather more hit and miss, and most promoters of daylight will be hard-pressed to place an actual *value* on daylighting. Not knowing the true value of a resource hardly puts one in a commanding position to convince others of its real worth. By not seeming to be interested in determining realistic measures of daylighting, daylight practitioners have, I believe, unwittingly communicated to others in the design team a sense that daylight is not really as important as their rhetoric would suggest. Whilst the thermal and airflow practitioners make ready use of the latest research developments to advance their expertise in building performance evaluation, their daylighting colleagues, in the main, find no fault in using a fifty year old technique that ignores the effect of climate on illumination.

How did we get here?

The thermal modelling community readily embraced the possibilities offered by programs that could simulate the dynamic thermal response of buildings to climate when they first became available over twenty years ago. In part, this was because many of the practitioners who habitually used the steady-state prediction methods were well aware of their limitations - they had no compunction in ditching the old methods when better ones came along.

The situation with daylight modelling is markedly different. The majority of daylighting practitioners, and indeed researchers, seem quite satisfied with the daylight factor. Aside from a small number of exceptions [Kendrick 1980] [Tregenza 1980], the fundamental basis of the daylight factor has gone largely unquestioned. It seems that, at the outset, the daylight factor gained acceptance as *the* evaluative scheme without the scrutiny and debate in peer-reviewed journals that one normally expects in science and engineering. The author has tried to trace the origin of the daylight factor but thus far has failed to unearth what might be called a seminal 'first' paper or treatise in a peer-reviewed journal. Standard texts such as Hopkinson's book on Lighting (Architectural Physics) present the daylight factor as the established technique and make mention only of various HMSO tables and recommendations [Hopkinson 1963]. The daylight factor may well have its origins in the sky factor approach that was promoted by Percy Waldram nearly a century ago. What the daylight factor shares with the sky factor is the notion that the evaluation of daylight should be based on relative rather than absolute values:

> *As early as 1909 he [Waldram] was proposing that interior daylight illumination should be expressed not as an absolute value, but as a proportion of that simultaneously available from the dome of the unobstructed sky.* [Chynoweth 2005]

This notion seems to have become an *idee fixe* for daylighting researchers and practitioners ever since. In part this may be due to the authority and esteem in which Percy Waldram was held. The notion is founded on the belief that the human eye adapts to changing levels of external illumination. Whilst there is certainly truth in this, the suitability of illumination for tasks ultimately depends, of course, on absolute values. How Waldram related the sky factor to measures of absolute illumination was never made clear, and Waldram himself gave conflicting reports on this. Chynoweth's fascinating paper on the origins of Waldram's recommendations for acceptable values of the sky factor has unearthed some startling facts regarding both the methods employed and the conclusions drawn [Chynoweth 2005]. There is not the space here to expand on this; readers interested to learn more are urged to read Chynoweth's paper. Significant amongst Waldram's legacies is his recommendation of the 0.2% sky factor as the point at which "reasonable" people would become dissatisfied with the illumination in a room. This so-called "grumble point" became enshrined in rights to light disputes, and it is still used today even though it equates, in the main, to exceedingly low levels of absolute illumination. What is surprising is that Waldram's recommendation seems to have been accepted without much critical scrutiny, and, even more surprisingly, that the methodology used went largely unquestioned for so long.

One senses that something not too dissimilar may have transpired with regard to the ready acceptance and continued routine use of the daylight factor. The fundamentals of daylight modelling have changed little over the past fifty years. The daylight factor exists not simply as an evaluation method; its use over the past half century has resulted in what might be called a 'daylight factor mindset'. By this it is meant a fixed mental attitude or disposition that predetermines a response to a new problem or situation. The mindset is characterised by the tendency to routinely constrain the evaluation scenario so that only a single sky luminance pattern is considered (or at best, a very small number of them). The literature offers many examples of this mindset and a few are listed here. References are not given since the purpose is to illustrate a general propensity rather than pick out specific papers. Firstly, it is depressingly common to see daylight factor studies carried out routinely for almost any locale in the world. Rarely is a scintilla of qualification given as to the appropriateness of the CIE standard overcast sky conditions for the locale under evaluation, e.g. Dubai. Daylight glare indices have been calculated for static (CIE overcast) sky conditions when any realistic measure must surely make account of the likelihood for glare under realistic, time-varying climatic conditions (including sun). Daylight factors have been used to analyse the performance of light-redirecting devices (e.g. mirror light shelves) when it is evident that any measure of their true effectiveness must account for the capacity to redirect sunlight deep into the space (and indeed to offer shading near to the window). A few studies have used the CIE clear sky distribution (with sun) in an attempt to make some analysis of illumination at a particular time of the year, often the summer solstice. But what about the other thousands of sky and sun configurations (that can be readily elucidated from climate data) that were measured for that locale?

Daylight factors and LEED: the failure of good intentions?

The Leadership in Energy and Environmental Design (LEED) scheme is promoted by the US Green Building Council to encourage, amongst other things, the design of low energy buildings. Daylight is one of the considerations in the determination of a LEED credit rating. The requirement for LEED credit 8.1 is phrased as follows: "Achieve a minimum Daylight Factor of 2% (excluding all direct sunlight penetration) in 75% of all space occupied for critical visual tasks" [USGBC 2005]. The note in parentheses that all direct sunlight penetration should be excluded is somewhat vague since LEED recommends a standard daylight factor calculation which, of course, makes no account of sunlight, direct or otherwise. Perhaps it is implied that designers should strive to eliminate "all direct sunlight penetration", but there seem to be no mandatory requirements to assess this. And indeed the LEED guidelines suggest the use of various "best practice" shading devices which implies that direct sun is expected at least some of the time.

The example used in this paper presents an interesting case when the LEED criteria are applied. Only the unshaded Basecase building would attain the LEED credit for daylight: a DF of 2% is achieved across 81% of the floor area. With the addition of shading in variants 1 and 2, the 2% DF value is achieved across 72% and 64% of the floor area, respectively. In other words, the shading needed to lessen the propensity for high illuminances (with the associated discomfort and solar gains) would, for this building, cause it to fail to achieve the LEED daylight credit.

Recall that the illuminances for the light-well example used UK climate data (London), whereas the LEED DF rating applies without modification to *all* of the states in the US - from rainy Seattle to sunny Miami. If the unshaded Basecase produces internal illuminances that are often too high for comfort under UK climate, how much worse will the conditions be when this building is exposed to the Miami climate? There is now a growing concern in the US that the daylight factor basis of LEED is promoting the design and construction of buildings that are over-glazed, and that the cooling costs for these buildings are likely to outweigh whatever savings that may result from daylight. In fact, providing too much daylight could well result in increased usage of electrical lighting as the blinds are likely to remain drawn much of the time. To the onlooker uninitiated in the habits and beliefs of the traditional daylight practitioner, the notion that a climate-insensitive parameter could play a role in determining either the form of a building or the construction of its facade must seem very strange indeed. Particularly so when this parameter is applied uniformly across a continent that experiences such extremes in prevailing climatic conditions.

Summary

Whilst some of the applications for climate-based modelling might be considered futuristic (e.g. performance evaluation of electrochromic glazing), the majority are problems of today. In fact, the three examples given in this paper offer solutions to problems that daylight practitioners have been confronted with for decades. Determining measures of: solar access/injury, the cumulative exposure of art works to natural light, or the true daylighting potential of buildings are all problems that have existed for some time. In fact, the vast majority of commonplace daylighting problems can be better solved through the application of climate-based techniques than the standard approaches. Thus there is no need to invent new daylighting problems to justify the use of climate-based approaches - todays problems provide sufficient reason. Impartial observers that have been convinced of the value of climate-based daylighting may feel that the onus to justify the method used should rest more heavily on those that continue to rely on the daylight factor.

Acknowledgments

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