Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Energy and Buildings 38 (2006) 905–913
ENERGY and BUILDINGS
www.elsevier.com/locate/enbuild

Useful daylight illuminances: A replacement for daylight factors

Azza Nabil, John Mardaljevic *

Institute of Energy and Sustainable Development, De Montfort University, The Gateway, Leicester LE1 9BH, UK

Abstract

This paper describes the application of a new paradigm, called useful daylight illuminance (UDI), to assess daylight in buildings. The UDI paradigm is designed to aid the interpretation of climate-based analyses of daylight illuminance levels that are founded on hourly meteorological data for a period of a full year. Unlike the conventional daylight factor approach, a climate-based analysis employs realistic, time-varying sky and sun conditions and predicts hourly levels of absolute daylight illuminance. The conventional approach produces a single number – the daylight factor as a percentage – for each evaluation point in the space. In contrast, a climate-based analysis results in an illuminance prediction for every daylight hour of the year for each point considered. The UDI paradigm offers a way to reduce the voluminous time-series data to a form that is of comparative interpretative simplicity to the daylight factor method, but which nevertheless preserves a great deal of the significant information content of the illuminance time-series. The UDI paradigm informs not only on useful levels of daylight illuminance, but also on the propensity for excessive levels of daylight that are associated with occupant discomfort and unwanted solar gain. In a conventional analysis of daylight provision and solar penetration, the two phenomena are assessed independently using methods that are idealised (daylight factor) and qualitative (shadow patterns). The UDI paradigm offers a simple methodology whereby daylight provision and levels of solar exposure are quantified using a single evaluative schema. Thus, it is also well-suited for teaching purposes. Application of the UDI paradigm is demonstrated using an analysis of design variants for a deep-plan building with a light-well. Comparison is made with the conventional daylight factor approach, the LEED daylight credit and measures of daylight autonomy.

Keywords: Daylight; Simulation; Shading

1. Introduction

The exploitation of daylight is recognised as an effective means to reduce the artificial lighting requirements of non-domestic buildings. In practice however, daylight is a greatly under-exploited natural resource. Significant amongst the various reasons for this may be the lack of realism of the standard predictive method: the daylight factor approach. A new schema to assess daylighting potential was introduced by the authors in a recent paper [1]. Called useful daylight illuminance (or UDI), the schema preserves much of the interpretive simplicity of the familiar daylight factor approach. Useful daylight illuminance however is determined from absolute values of time-varying daylight illumination for a period of a full year. This method of daylight illuminance modelling we call 'climate-based' since the (hourly) sun and sky conditions are founded on values from annual climate datasets (e.g. direct normal irradiance and global horizontal irradiance from TMY2 files). The idea of daylight autonomy has been used by others to evaluate the illuminance predictions from climate-based analyses [2]. Daylight autonomy is a measure of how often (e.g. percentage of the working year) a minimum work plane illuminance threshold of 500 lx can be maintained by daylight alone. In contrast, the UDI scheme is founded on a measure of how often in the year daylight illuminances within a *range* are achieved. Real daylight illuminances in buildings vary enormously, much more than is suggested by variations in predicted daylight factors. Notions of illuminance uniformity that are a legacy of the traditional daylight factor approach are therefore inapplicable for realistic, daylit conditions. Likewise, the notion of simply achieving a threshold illuminance (i.e. daylight autonomy) has restricted value for two reasons. Firstly, daylight autonomy fails to give significance to those daylight illuminances that are below the threshold (for example, 500 lx), but which are nevertheless known to be valued by occupants and also have the potential to displace all or part of the electric lighting. Secondly, daylight autonomy makes no account of the *amount* by which the threshold illuminance was exceeded at any particular instant. This is significant because high levels of daylight illuminance

* Corresponding author. Tel.: +44 116 257 7972; fax: +44 116 257 7981.
E-mail address: jm@dmu.ac.uk (J. Mardaljevic).

0378-7788/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.enbuild.2006.03.013

are known to be strongly associated with occupant discomfort. Thus, in contrast to daylight autonomy, the useful daylight illuminance scheme incorporates factors that are indicative of the propensity of occurrence for occupant discomfort.

Useful daylight illuminances are defined as those illuminances that fall within the range 100–2000 lx. The range used to define the limits of useful daylight illuminance is based on a comprehensive review of the latest data from field studies of occupant behaviour under daylit conditions. The UDI scheme is applied by determining the occurrence of daylight illuminances that:

1. Are within the range defined as useful (i.e. 100–2000 lx);
2. Fall short of the useful range (i.e. less than 100 lx);
3. Exceed the useful range (i.e. greater than 2000 lx).

Thus, only three metrics are used to characterise the hourly-varying daylight illuminances for an entire year at each of the calculation points. How this range was arrived at is described in the following section. Then follows the application of UDI to evaluate design variants for a large open-plan building with a central light-well.

2. Useful daylight illuminances

Real daylight illuminances across the workplane exhibit large variations both spatially and temporally. For example, daylight illuminances typically diminish rapidly with increasing distance from windows. Equally, daylight illuminances at a point can vary greatly from one moment to the next due to changing sun position and/or sky conditions. As noted, conceptions of illuminance uniformity that arise from using the standard overcast sky approach are inapplicable for realistic conditions where the contribution of direct sunlight results in large differences between the maximum and minimum daylight levels. Consequently, any proposed metric that is devised to take account of realistic time-varying daylight illuminances must, in some way, cater for the large range in naturally occurring daylight levels. This can best be achieved by relinquishing the notion of a threshold (or target) illuminance, i.e., 500 lx value. In place of a threshold value, we propose that a measure of the occurrence of a range of illuminances that can be said to constitute *useful* levels of illumination provides a more informative metric. If the daylight illuminance is too small (i.e. below a minimum), it may not contribute in any useful manner to either the perception of the visual environment or in the carrying out of visual tasks. Conversely, if the daylight illuminance is too great (i.e. above a maximum), it may generate visual or thermal discomfort, or both. Illuminances that fall within the bounds of minimum and maximum are called here useful daylight illuminances. The absolute values assigned to the minimum and maximum illuminance levels are based on a review of published work on occupant behaviour in daylit office environments under a wide range of illumination conditions. The process detailing how the minimum and maximum illuminance levels were arrived at is described in the following section.

2.1. An overview of findings on occupant response to varying levels of daylight illumination

It is acknowledged that there is a large range of lighting conditions over which the human eye performs satisfactorily, and that there is a large range of variation among individuals as to what comprises satisfactory visual conditions. Whilst there are no absolutely conclusive studies that correlate daylighting provision or occupant satisfaction with worker productivity, there is mounting evidence that workers do appreciate offices that provide daylight and a view of the outside, and that glare-free and thermally comfortable spaces have quantifiable effects on workers satisfaction and performance [3,4].

The UK Chartered Institution of Building Services Engineers (CIBSE) Code for Interior Lighting recommends that offices should have a design illuminance level of 500 lx. A design illuminance of 500 lx is, in fact, commonplace throughout much of the developed world. Consequently, electric lighting is usually designed to deliver 500 lx of (artificial) illuminance evenly across the workplane. When sufficient daylight is available, electric lighting may be reduced, or switched off altogether, by either the occupants themselves or some control mechanism.

The Cost-Effective Open-Plan Environment (COPE) field study, conducted by the Institute for Research Construction (National Research Council Canada) recorded that illuminances larger than, or equal to, 150 lx were classified as appreciable daylight [5]. Furthermore, the Illuminating Engineering Society (IES) of North America recommends 50–100 lx, provided directly onto the individual task area, as the general range of illuminance required for working with CRT screens in laboratory areas [6]. In fact, during a survey of the work spaces of a computer hardware and software distribution company, where each of the offices contained at least two computers, measurements showed that most employees felt comfortable with a lighting level of around 100 lx (as opposed to the standard regulations of workplaces demanding 300–500 lx at desk level) [7]. It has also been observed that people tend to tolerate much lower illuminance levels of daylight than artificial light, particularly in diminishing daylight conditions at the end of the day, such as continuing to read at daylight levels as low as 50 lx [8].

In a field study carried out by Lawrence Berkeley National Laboratory (USA), office workers were allowed to create their own lighting environment by manually controlling blade angles of mechanical Venetian blinds and varying the intensity of electric lighting. The illuminances recorded during the study were in the range 840–2146 lx in the morning and 782–1278 lx in the afternoon. This indicated that the occupants either preferred or, at least, tolerated higher light levels than those set by the automatic control system (510–700 lx) [3].

Studies relating to office workers' impressions of daylight and lighting signified that most office occupants wanted to work under some form of daylighting. However, in heavily glazed offices, people were often less satisfied due to the high levels of daylight provision and the associated propensity for discomfort [9]. While noting that satisfaction with daylight is a complicated issue depending on many other factors such as facade orientation, obstructions, and the effectiveness of shading devices, levels of daylight that are considered too low may easily be supplemented by electric lighting, whereas levels that are too high are associated with problems that are more complex to deal with (for example, glare and overheating) [9]. In fact, occupant surveys have uncovered shortcomings for conventional design practice and have expanded the definition of an adequate office visual environment [10]. For example, variation in daylight levels is considered desirable provided that the range in experienced levels is not too great. Occupants prefer a space with a variation in the natural light pattern, and where they have a slightly higher task illuminance than the general surround illuminance, their visual perception can be enhanced [10]. Furthermore, researchers have noticed that lighting levels that are markedly higher than the typical design workplane illuminance level (for example, 500 lx) are tolerated by the occupants unless there is glare or direct sun, in which case the occupants may opt to operate a shading device [11]. Observations made by Roache over several weeks suggested that the visual environment, when facing a computer workstation which was at a right angle to the window (as is recommended), was reasonably comfortable when the workplane illuminance was below 1800 lx [9,12]. During that same experiment, it was noted that the daylight illuminance range of 700–1800 lx appeared to be acceptable for both computer and paper-oriented tasks.

The visual effects of lighting have been an area of investigation since the emergence of the science of optics hundreds of years ago. The physiological effects of illumination levels on humans, however, are a relatively recent area of study. Following the discovery in 2002 of novel photoreceptor cells in the eye, with additional nerve connections to the brain, it is now better understood how light influences and controls a large number of biochemical processes in the human body. Significant amongst these is the control of the biological clock and the regulation of important hormones through consistent light–dark rhythms. These studies have revealed that light has a significant influence on health, wellbeing, alertness, and even the quality of sleep that is much greater than was suspected only 25 years ago [13]. Additionally, several recent studies, such as that by Partonen and Lonnqvist [14], show that bright light exposure improves mood and reduces depressive symptoms among subjects working indoors, particularly in winter for locales with high latitudes. In fact, more and more studies are bolstering the notion that current indoor lighting levels and standards are too low for biological stimulation as well as for most peoples' preferences, and that the criteria for "good" lighting need to be reconsidered [13,15].

2.2. *UDI: the rationale for the range limits*

The review of the published findings on occupant preferences and behaviour described in the previous section is summarized as follows:

- Daylight illuminances less than 100 lx are generally considered insufficient either to be the sole source of illumination or to contribute significantly to artificial lighting;
- Daylight illuminances in the range 100–500 lx are considered effective either as the sole source of illumination or in conjunction with artificial lighting;
- Daylight illuminances in the range 500–2000 lx are often perceived either as desirable or at least tolerable;
- Daylight illuminances higher than 2000 lx are likely to produce visual or thermal discomfort, or both.

Thus, it is proposed that any daylight illuminance in the range 100–2000 lx should be considered as offering potentially useful illumination for the occupants of the space. When evaluating predicted time-varying daylight illuminances on the workplane, useful daylight illuminance is said to occur whenever the illuminances at a calculation point fall within the range 100–2000 lx.

2.3. *UDI modalities: cellular space and open-plan*

The UDI scheme can be applied in different ways depending on the evaluation scenario. At present, two UDI modalities have been formulated. Side-lit cellular office spaces with vertical glazing are a common configuration in many buildings. For these spaces it is usual for the occupants to control the levels of illumination using shades or blinds. Here, the upper limit of what constitutes UDI (i.e. 2000 lx) can be used as the threshold value which, when exceeded, is likely to cause the occupants to deploy some shading device (e.g. lower the blinds). For these spaces, UDI was defined to have been achieved whenever *all* the illuminances across the core of the work plane (at any one instant) were in the range 100–2000 lx [1]. This condition is consistent with occupant behaviour for these spaces where any one of the occupants may experience discomfort and deploy the shades.

For large, open-plan spaces the condition that UDI is achieved simultaneously across the work plane is too restrictive. For these spaces, especially when they are deep-plan, illuminances will rarely be in the range 100–2000 lx across all the work plane at any one instant. For these scenarios, we propose that the occurrence of UDI achieved, exceeded and fell-short is determined for each point independently of the others. This UDI modality was used to evaluate three design variants for a large, open-plan building with a central light-well. The building model and the prediction of internal daylight illuminances are described in the next section.

3. The building model and illuminance prediction

A simple 3D model of a four-storey open-plan building with a central light-well was constructed using *Radiance*[16] scripts and surface generators. The building model had the dimensions shown in Fig. 1. The reflectivities of the walls, ceiling, floor, and overhangs were set to be 0.5, 0.7, 0.3, and 0.7, respectively. The four facades had glazing 1.7 m high starting at a window

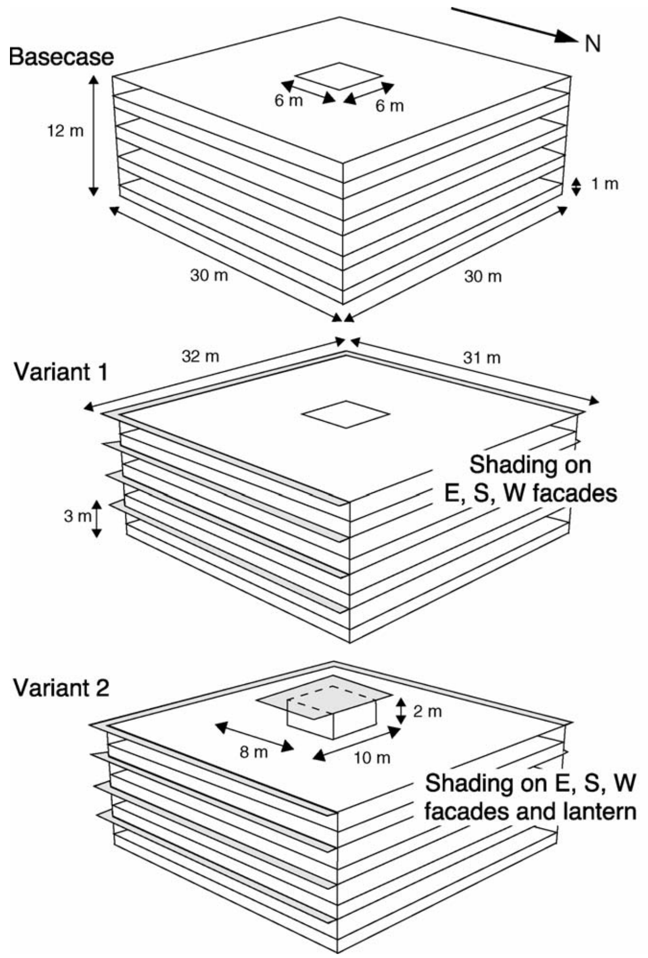

Fig. 1. Building model and design variants.

sill height of 1 m from the floor. The glazed facades and the light-well were modelled as double glazing with transmittance of 0.74 (0.806 transmissivity) corresponding to a composition of 6 mm Kappafloat inner pane and 6 mm outer clear float [17].

3.1. The design variants

The three scenarios, comprising a basecase and two external shading variants, were as follows:

- Basecase: all four facades and light-well were unshaded, i.e., no overhangs included in the model, with the top of the light-well glazed and flush with the rest of the building roof, as shown in the top diagram of Fig. 1.
- Variant 1: shading overhangs were added to the East, South, and West facades, where the thickness of the overhangs was 0.3 m starting at the top of the glazing at 2.7 m from the floor. The width of the overhangs was 1 m extending at right angles to the building facades, as shown in the middle diagram of Fig. 1. Overhangs were not deemed necessary on the North facade since only northern-hemisphere locales were considered in this study.
- Variant 2: in addition to the facade overhangs used for variant 1, a lantern was added to the top of the light-well. The height of the lantern was 1.7 m. The sides were glazed, and an opaque roof with shading overhangs extending 2 m on the East, South, and West sides was added, as shown in the bottom diagram of Fig. 1.

One of the aims of this study is to demonstrate how the UDI metrics can be used to rapidly evaluate several design options. Accordingly, we have used a fairly simple building model for the purpose of demonstration. The illuminance modelling is described in the next section.

3.2. Prediction of daylight factors and time-varying illuminances

For the examination of UDI given in this paper, the authors present results for the ground floor only. This is sufficient to demonstrate the application and effectiveness of the UDI scheme. A grid of 900 calculation points (30×30) was evenly distributed across the workplane (height 0.8 m) on the ground floor. These points represent the locations of the ‘virtual photometers’ used in the simulation, i.e., illuminances were predicted at each of these points. The distance between the walls and the edge points in the grid was 0.5 m, and the distance between consecutive points in both directions was 1 m.

The CIE standard overcast sky luminance pattern was used to predict daylight factors at the 900 calculation points across the ground floor workplane for each of the three design variants. The native *Radiance* calculation method was used.

For the climate-based analysis, where time-varying illuminances are predicted, the calculation method was based on Tregenza’s daylight coefficient (DC) approach [18]. Using the modified daylight coefficient scheme formulated and validated by Mardaljevic [19], and later refined by Nabil [20], daylight coefficients were computed for each of the 900 calculation points. *Radiance* was used as the ’engine’ to predict the daylight coefficients. Next, using the horizontal irradiation data in the CIBSE Test Reference Year (TRY) for London (51.38N, 0.78W), hourly sky and sun conditions were derived for every daylight hour in the year (i.e. when the irradiation is greater than zero). The sky model mixing function described in Mardaljevic [21] was used to determine the hourly varying sky luminance patterns. The hourly internal illuminance was derived from the pre-computed daylight coefficients at each of the 900 points for each of the three scenarios. The total number of illuminance values computed was: $4356(\text{daylight hours}) \times 900(\text{points}) \times 3(\text{scenarios}) = 11,761,200$. These data were processed to determine the three UDI metrics and also measures of daylight autonomy. A discussion of the three daylight assessment techniques using illuminances founded on climate data for London (UK) is described in the next section.

4. Results

The intention here is to compare the evaluative potential of the three daylight assessment techniques (daylight factors, daylight autonomy and useful daylight illuminance) through an examination of their sensitivity to changes in the building design. Thus, the results for the three techniques applied to the three designs are presented in groups of three by three (i.e. nine) plots. Two sets of plots were generated. The first group are false-coloured surface plots (or 'maps') that show the variation in the predicted daylight metrics across the workplane. The second group are line plots that give the size of the daylight metric along an East-West line across the centre of the building. The results are discussed first individually and then all together.

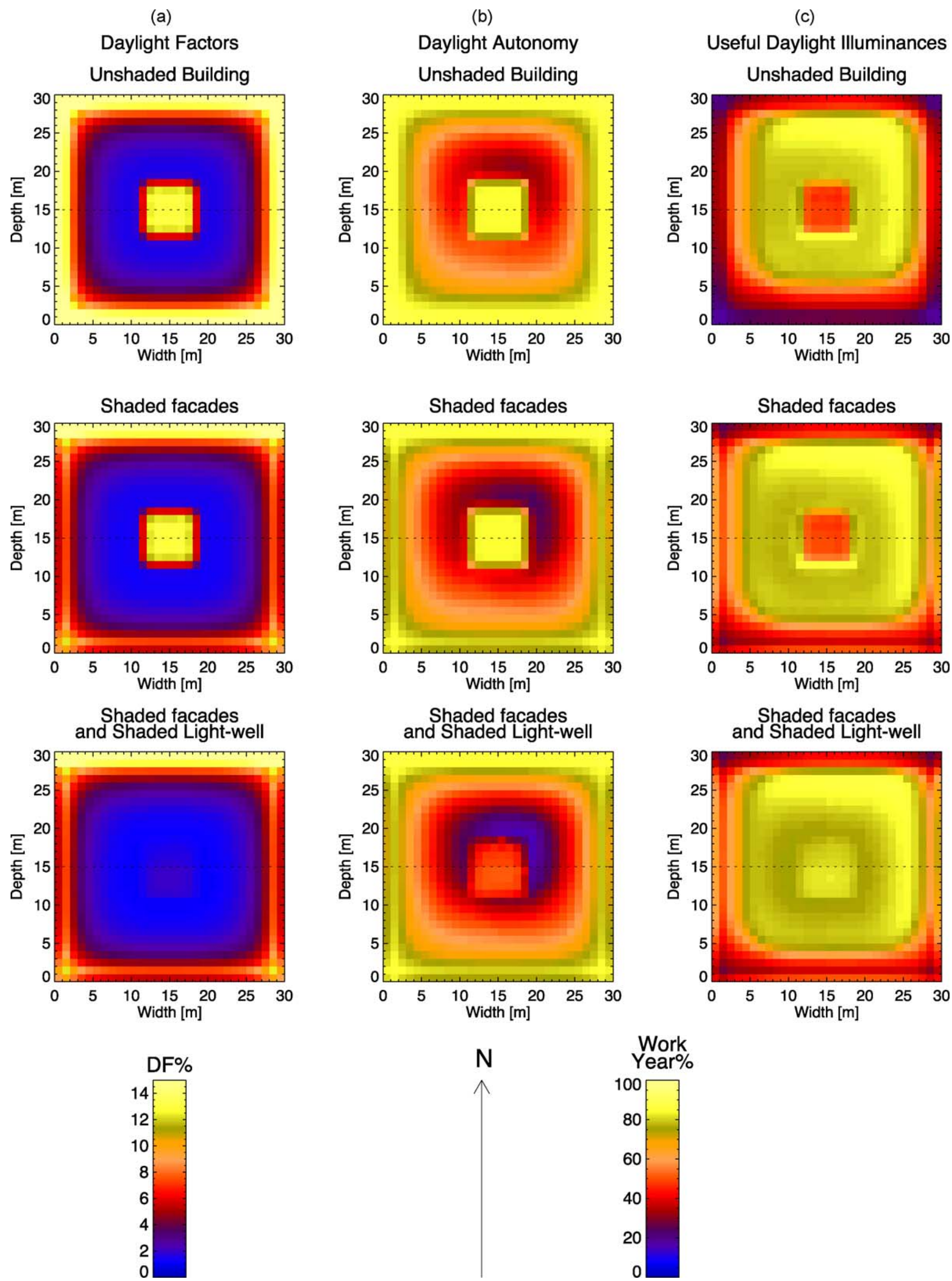

Fig. 2. Daylight factor, daylight autonomy and useful daylight illuminance area plots.

4.1. Daylight factors (for anywhere and everywhere)

The predicted daylight factors across the workplane for the three design variants are shown in the first column (a) of Fig. 2. The DF value is shown using colour (see the legend directly below the plots). The daylight factor along the dotted line running East-West is plotted as a curve in column (a) of Fig. 3.

The symmetry of the false colour map for the basecase (unshaded) building (Fig. 2, top of column (a)) results, of course, from the use of the standard overcast sky: daylight factors are, by definition, insensitive to the orientation of the building. It can be seen from the false colour maps and the line plots that daylight factors in the vicinity of all four facades, particularly in the corner areas, are much higher than deep inside the building. Within 2 m of the glazed facades, the DFs are equal to 10% or higher, decreasing gradually as the distance from the window increases. The DFs then start to recover in value about 1.5 m from the central area directly beneath the light-well, increasing sharply to peak of about 13%. The addition of exterior overhangs on the East, South, and West facades of the building in variant 1 (Figs. 2 and 3, middle of column (a)), reduces the DFs 2 m from facades to around 5.5%.

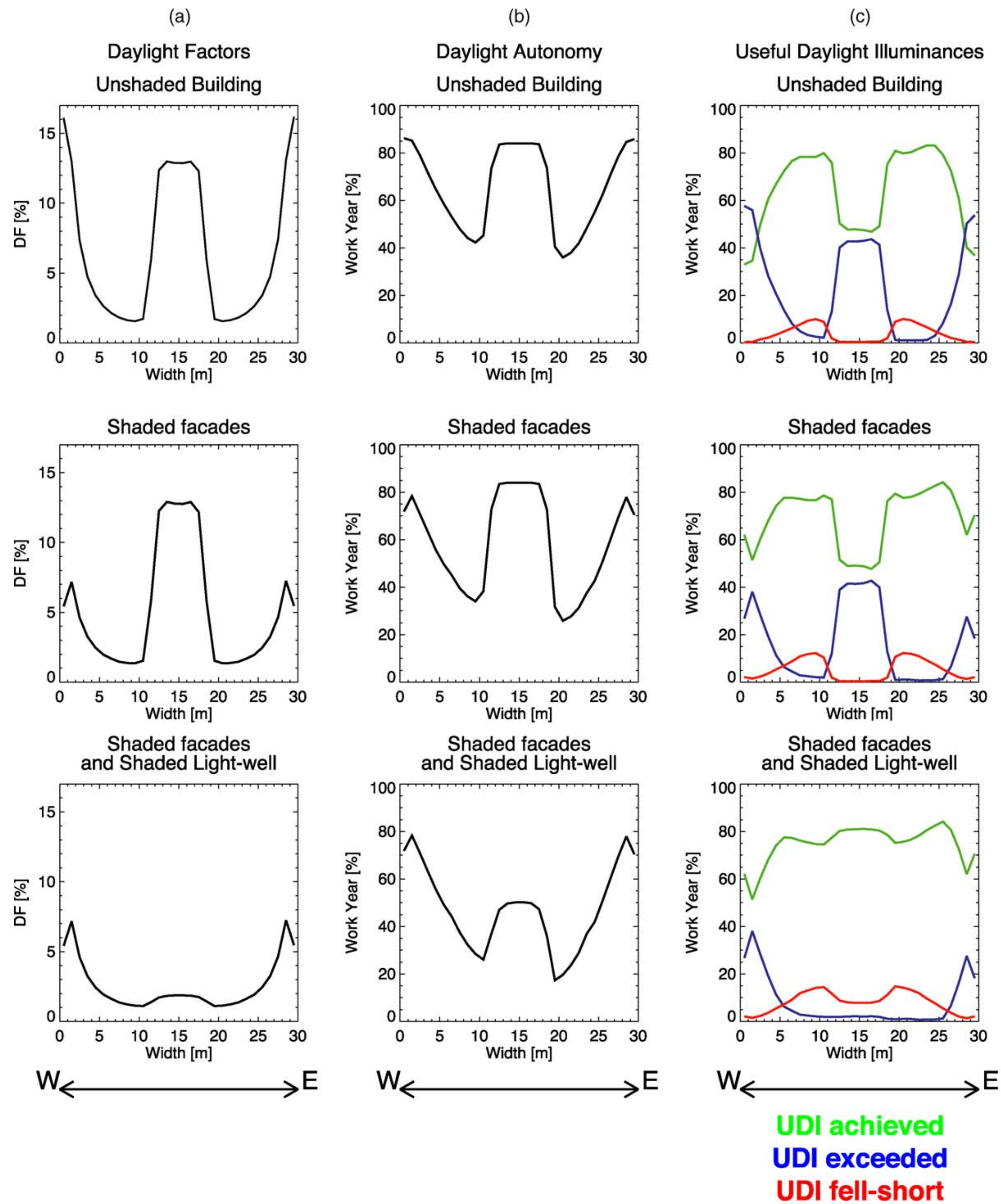

Fig. 3. Daylight factor, daylight autonomy and useful daylight illuminance line plots.

The addition of a lantern with overhangs at the top of the light-well in variant 2 (Figs. 2 and 3, bottom of column (a)) further decreases the DFs deep within the building so that the DFs never exceed 2%.

4.2. Daylight autonomy (London, UK)

Using the time-varying illuminances derived from the London climate file, daylight autonomy (DA) during the 'working year' (i.e. between the hours 09:00–18:00) was calculated at each of the 900 calculation points on the ground floor workplane. The DA results for the three variants are given alongside those for the daylight factors. That is, the false colour DA maps shown in column (b) of Fig. 2, and the line plots in column (b) of Fig. 3. Note that daylight autonomy and UDI are both expressed in terms of the percentage of the working year. Thus, they share the same legend which is positioned between the two respective columns in Fig. 2.

Reading from the false colour maps and line plots, DA (i.e. 500 lx or greater) is achieved more than 80% of the working year in the vicinity of all four facades (within 2 m of the glazing). This is especially so for the corners areas, and also within the central area of the ground floor directly beneath the light-well in the basecase. Similar to the DF results, DA decreases for points farther away from the glazed facade. However, unlike DFs, the pattern of illuminance in the four quadrants of the ground floor of the unshaded building in the base case is not symmetrical, with the North-East quadrant exhibiting the biggest drop in illuminance away from the windows. The shading of three facades with overhangs in variant 1 (middle of column (b) in Figs. 2 and 3) causes a noticeable reduction in DA. Shading from the lantern in variant 2 causes the DA in the central part of the ground floor to drop from about 85% to around 50% or less. In a detailed analysis, the user-controlled operation of blinds in response to high levels of illuminance could be estimated and modelled [2]. This would reveal how the deployment of blinds at the perimeter can impact on the quantity and distribution of daylight in the core of the space. However, the purpose of the comparison of DA with UDI made here is to reveal how each acts an indicator of the *intrinsic* daylighting performance of the space.

4.3. The UDI metrics (London, UK)

The same illuminance data used to determine daylight autonomy were re-processed to determine the occurrences in the working year when UDI was: achieved, exceeded and fell-short. This was done for predictions at each of the 900 calculation points on the workplane. To save space, only the false-colour maps for UDI achieved are given in Fig. 2(column (c)). However, the curves for the UDI exceeded and fell-short metrics are given in the line plots Fig. 3(column (c)).

The false colour map of achieved UDI for the unshaded building (top of column (c) in Fig. 2) shows minimum values around the perimeter of the building. It is evident from the corresponding line plot in Fig. 3 that this is due largely to UDI being exceeded, and that this occurs for up to 60% of the working year. The same is true, albeit to a slightly lesser degree, for the central area under the light well.

For variant 1, the addition of overhangs on the three facades (middle of column (c) in Figs. 2 and 3) reduces the UDI exceedance in the perimeter areas. This is particularly so for the East and West facades where UDI is now achieved for more than 50% of the working year. Although the corner areas and the south facade also witness an improvement in UDI with the introduction of overhangs, it is to a lesser degree: UDI is achieved here for about 35–40% of the work year. The addition of a lantern with an opaque roof and overhangs (variant 2) improves the metric considerably for the central workplane area directly beneath it. UDI is now achieved for over 75% of the working year, and exceedances of UDI are greatly reduced.

4.4. A comparison of DFs, DA and UDI

The most striking feature of the plots across the top row of Fig. 2 is the symmetry of the DF distribution alongside the asymmetry of the DA and UDI distributions. The DF, of course, is insensitive to the glazing orientation. However, the DF and DA plots share a similar character in the overall form of the distributions: highest values around the perimeter and under the lantern. The UDI distribution however follows a pattern that is almost the inverse of the DF or DA patterns: the UDI is a minimum around the perimeter and under the lantern.

Moving on now to variant 1 (shading on the East, West and South facades), there is a reduction in both the DF and the DA for the perimeter areas where shading was introduced. In contrast, the achieved UDI for these perimeter areas *increases* quite markedly (middle row of plots in Fig. 2). It can be seen in the respective line plots (Fig. 3) that the increase in achieved UDI is due mostly to the reduced occurrence in UDI exceedances resulting from the introduced shading.

A similar change in the pattern of DA and UDI is noticed for the central region with the introduction of the lantern (with opaque top and shading overhangs). There is a marked reduction in DF and DA under the lantern, and a significant increase in UDI (bottom row of plots in Fig. 2). Again, the line plots reveal that the increase in UDI is due to reduced exceedances (i.e. lower occurrence of illuminances greater than 2000 lx).

To summarise, the highest level of daylight autonomy (and the highest daylight factors) are indicated for the basecase building without shading. The UDI exceedance plot for the basecase reveals that illuminances greater than 2000 lx are expected for around 60% and 40% of the working year for perimeter and central areas, respectively. Occupant studies suggest that these levels of illumination will produce discomfort for significant periods of the year. They are also likely to be indicative of high levels of solar gain. In contrast, the highest levels of UDI are achieved for the variant 2 design that has perimeter and lantern shading.

4.5. LEED, DFs and UDI

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’’ [22]. 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 approximately 80% 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. This strongly suggests that the basis for the LEED daylight rating might warrant reconsideration, and that further comparison with climate-based analyses is advised.

5. Discussion

The UDI scheme is both informative and disarmingly simple. It is only marginally more complex than the daylight autonomy method, but it nevertheless gives a much greater insight into the spatio-temporal dynamics of daylight illumination. In particular, it gives an indication of the propensity for high levels of illumination that are associated with discomfort and solar gains. Key to this is the use of a range of illuminations that is founded on human factors, rather than the single threshold value which is designed specifically for energy calculations (i.e. daylight autonomy). Although UDI is based primarily on human factor considerations, high values of achieved UDI might well be associated with low energy usage for electric lighting, and possibly also for cooling. In the first UDI paper, we reported a strong anti-correlation between electric lighting usage and achieved UDI for cellular office spaces with user controlled shades [1]. That analysis employed the other UDI modality where, to achieve UDI at any one instant, each point in the work plane had to be within the UDI range (see Section 2.3). UDI is a very recent concept and further studies need to be carried out to determine if high levels of achieved UDI are indeed an indicator of low electric lighting usage for the majority of building scenarios. The implications for cooling requirements also need to be determined.

Fifty years since it was first proposed, the DF persists as the dominant evaluation metric because of its inherent simplicity rather than its realism. For the vast majority of practitioners, the consideration of *any* quantitative measure of daylight begins and ends with the daylight factor. Despite the evident lack of realism, practitioners have become accustomed to the daylight factor and various standards/criteria (e.g. LEED) are framed only in terms of daylight factors. There is little doubt that time-varying illuminance predictions, i.e., climate-based modelling, offer a far more realistic account of true daylighting conditions than the highly idealised daylight factor approach. The UDI scheme offers the means to communicate the significant characteristics of climate-based analyses in a concise and readily intelligible form. Furthermore, the UDI metrics provide a more informative and comprehensive assessment of daylight conditions than that which can be gained from daylight autonomy. Additionally, we envisage significant potential for UDI in the teaching of effective daylighting design principles. Students are currently taught that the assessment of daylight and solar penetration should be carried out using essentially incompatible methods: overcast sky for daylight and shadow patterns for solar penetration. The UDI approach provides a unified, holistic scheme to make simple, yet meaningful assessment of daylight and solar penetration *together* using realistic, climate-based conditions that are specific to the locale for the building. It is hoped that the UDI scheme will help to promote the wider use of climate-based modelling to assess daylight in buildings.

Acknowledgements

This work was carried out in support of the activities of the International Energy Agency's Task 31, ‘‘Daylighting buildings in the 21st Century’’.

References

[1] A. Nabil, J. Mardaljevic, Useful daylight illuminance: a new paradigm for assessing daylight in buildings, Lighting Research and Technology 37 (1) (2005).

[2] C.F. Reinhart, Lightswitch-2002: a model for manual and automated control of electric lighting and blinds, Solar Energy 77 (1) (2004) 15–28.

[3] E. Vine, E. Lee, R. Clear, D. DiBartolomeo, S. Selkowitz, Office workers response to an automated Venetian blind and electric lighting system—a pilot study, Energy and Buildings 28 (2) (1998).

[4] S. Selkowitz, High performance glazing systems—architectural opportunities for the 21st century, in: Proceedings of Glass Processing Days (GPD) Conference, Tampere, Finland, 1999.

[5] C.F. Reinhart, Effects of interior design on the daylight availability in open plan offices, in: Conference Proceedings of the ACEEE Summer Study on Energy Efficient Buildings, 2002, pp. 1–12.

[6] IES, Outline of a Standard Procedure for Computing Visual Comfort Ratings for Interior Lighting lm-42-72, Illuminating Engineering Society (IES) of North America, 1991.

[7] M. Schuler, Building simulation in application: developing concepts for low energy buildings through a co-operation between architect and engineer, in: Proceedings of the Solar World Congress, the International Solar Energy Society (ISES), Harare, Zimbabwe, 1995.

[8] N. Baker, We are all outdoor animals, in: Proceedings of PLEA 2000, Cambridge, 2000.

[9] L. Roache, E. Dewey, P. Littlefair, Occupant reaction to daylight in offices, Lighting Research and Technology 32 (3) (2000).

[10] S. Selkowitz, M. Rubin, E.S. Lee, R. Sullivan, A review of electrochromic window performance factors, in: Proceedings of the SPIE International

Symposium on Optical Materials Technology for Energy Efficiency and Solar Energy Conversion XIII, Freiburg, Germany, 1994.

[11] E.S. Lee, D.L. DiBartolomeo, S. Selkowitz, The effect of Venetian blinds on daylight photoelectric control performance, Journal of the Illuminating Engineering Society 28 (1) (1999).

[12] L. Roache, Summertime performance of an automated lighting and blinds control system, Lighting Research and Technology 34 (1) (2002).

[13] W.J.M. van Bommel, G.J. van den Beld, Lighting for work: a review of visual and biological effects, Lighting Research and Technology 36 (4) (2004).

[14] T. Partonen, J. Lonnqvist, Bright light improves vitality and alleviates distress in healthy people, Journal of Affective Disorders 57 (1–3) (2000).

[15] S.H.A. Begemann, G.J. den Beld, A.D. Tenner, Daylight, artificial light, and people in an office environment: overview of visual and biological responses, International Journal of Industrial Ergonomics (1997).

[16] G. Ward Larson, R. Shakespeare, Rendering with Radiance: The Art and Science of Lighting Visualization, Morgan Kaufmann, San Francisco, 1998.

[17] Pilkington Glass Ltd., Glass and Transmission Properties of Windows, Environmental Advisory Service, 1991.

[18] P. Tregenza, I.M. Waters, Daylight coefficients, Lighting Research and Technology 15 (2) (1983) 65–71.

[19] J. Mardaljevic, The simulation of annual daylighting profiles for internal illuminance, Lighting Research and Technology 32 (3) (2000).

[20] A. Nabil, Performance modelling for advanced envelope systems, Ph.D. Thesis, De Montfort University Leicester, 2002.

[21] J. Mardaljevic, Daylight simulation: validation, sky models and daylight coefficients, Ph.D. Thesis, De Montfort University Leicester, 2000.

[22] The U.S. Green Building Council, Leed: Leadership in Energy and Environmental Design, 2005.