Multi-Scale Daylight Modelling For Urban Environments

John Mardaljevic^a and George M. Janes^b

^aSchool of Civil & Building Engineering,
Loughborough University,
Loughborough, Leicestershire, LE11 3TU, UK
e-mail: j.mardaljevic@lboro.ac.uk
Web: [Loughborough Staff Page](#)
Tel: +44 1509 222630

^bGeorge M. Janes & Associates,
250 East 87th Street, Fifth Floor,
New York, NY 10128, USA
e-mail: george@georgejanes.com
Web: <http://www.georgejanes.com/>
Tel: +1 646 652 6498

Contents

1	Introduction	4
2	Background	4
2.1	Climate and microclimate	4
2.2	The urban solar microclimate	5
2.3	The USM and human experience	6
2.4	The USM in guidelines and recommendations	7
2.5	‘Real’ climate	8
2.6	Climate-based daylight modelling	9
3	Visualising the urban solar micro-climate	10
3.1	The San Francisco 3D model	10
3.2	Harvesting solar energy	11
3.3	A strategic evaluation of urban solar potential	13
3.4	Irradiation mapping of ‘virtual London’	14
4	The ASL building: A solar access study	15
4.1	Density and zoning in New York City	15
4.2	The Art Students League building	17
4.3	Quantifying the potential daylight injury	17
4.4	Outcomes and implications	20
5	Daylighting the New York Times Building	22
5.1	3D model for NYT building and surroundings	22
5.2	The spatio-temporal dynamics of sunlight exposure	23
5.3	Balancing daylight provision and visual comfort	24
6	Summary	27
7	Acknowledgements	28

List of Figures

1	Illuminance data from a standardised climate file for Nottingham, UK . . .	8
2	3D model of San Francisco	11
3	Five views of the San Francisco 3D model showing the predicted total annual irradiation	12
4	Strategic evaluation of solar potential for the San Francisco 3D model . . .	13
5	Map showing the predicted total annual irradiation for central London overlaid on aerial photograph	16
6	Art Students League Building (right) with adjacent lot	18
7	Existing and proposed arrangement of buildings - skylights marked in blue and ringed	19
8	Total annual illumination incident at the skylights for the existing and proposed cases	20
9	Renderings of the NYT building and surrounding context - three views showing effective magnifications of x1, x10 and x100	23
10	Spatial and temporal exposure maps for the NYT building	25
11	Simulated plan view showing the position and view direction for the twelve ‘window commissioning’ viewpoints, i.e. wc01 to wc12	26
12	Annualised profiles for field-of-view luminance (floor 26, wc04) and illuminance at the work station.	27

List of Tables

1	Facade area (m^2) graded for total annual irradiation and height above ground level for the San Francisco model (see Figure 4).	14
2	Predicted change in total annual illuminance (TAIL) caused by the proposed building	19

1 Introduction

Daylight in buildings is the natural illumination experienced by the occupants of any man-made construction with openings to the outside. The quantity and quality of daylight in buildings is continually varying due to the natural changes in sun and sky conditions from one moment to the next. In urban settings, the dynamics of daylight illumination are amplified by the vertical extent of buildings and the density of the built form. Traditional schema for evaluating daylight in the built environment consider only one or perhaps a few ‘snapshot’ conditions, e.g. a single overcast sky, or a sequence of shadow patterns for selected hours. This chapter describes the application of a technique called climate-based daylight modelling (CBDM) across various urban scales – from office spaces to large-scale city models. 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. Climate-based modelling delivers predictions of absolute quantities (e.g. illuminance) that are dependent both on the locale (i.e. geographically-specific climate data is used) and the building orientation (i.e. the illumination effect of the sun and non-overcast sky conditions are included), in addition to the building’s composition and configuration. The examples described in this chapter include theoretical studies and two ‘live’ projects.

2 Background

2.1 Climate and microclimate

Microclimate is a commonly used term, but just as is the case with the word ‘climate’, the meaning is multifarious and therefore lacking precision. The dictionary definition of climate gives the following:

Climate – the meteorological conditions, including temperature, precipitation, and wind, that characteristically prevail in a particular region.

As is evident from the definition quoted above, climate is not characterised by one specific measurable quantity. Rather, it is taken to be a combination of several physical quantities. Temperature perhaps is what first springs to mind when one thinks of climate. The phrase ‘historical temperature record’ is generally used to refer to the time from which reasonably reliable records exist, i.e. data founded on actual observations taken with accurate thermometers. This is generally considered to be from about 1850 – earlier records exist, but coverage and instrument standardisation are poorer. Note that atmospheric pressure has been accurately recorded over a similarly long period. However its primary purpose was to gain an understanding of the dynamics of weather systems, i.e. forecasting. Rainfall is relatively easy to measure, as is wind speed and wind direction. Solar radiation – the principal driver of the Earth’s weather system – is however difficult to measure. The amount of solar radiation resulting from the sky and sun at any one instant is characterised by a quantity called the global horizontal irradiance. This is a measure of the energy density incident on a horizontal surface and it has units of Watts per metre squared (Wm^{-2}). Note that the orientation of the surface is important. A horizontal surface is specified in the definition of global (horizontal) irradiance because it receives radiation from the entire hemisphere of sky. Radiation from the sky is called diffuse because it originates from all directions above the horizon. Cloudy skies without sun

produce mainly diffuse radiation (i.e. producing soft shadows). On clear days however the sun is often the dominant source of radiation, resulting in sharp, high-contrast shadows. To distinguish between radiation originating from the sky and sun it is necessary to measure the components separately. The sky component is called the diffuse horizontal irradiation. This can be measured in the same way as global horizontal irradiation with the addition of a ‘shadow band’ to block any (direct) solar radiation. The direct solar radiation is usually characterised by measurements of direct normal irradiance. To achieve this, the measuring instrument must track the movement of the sun to ensure that it is always pointing at the solar disc.

Microclimate is commonly taken to be that which occurs in ‘local zone’ where the climate differs from what is generally prevailing. Microclimates exist across a vast range of scales, e.g. a crevice in a rock, a walled garden, a sheltered meadow, etc. In each case, one or more components of the climate differ from what would otherwise be the case. For example, a walled garden would allow access to sun from the south, whilst sheltering plants from wind and the full sky hemisphere which can have very low radiative temperatures on clear nights. The ancient Persians, masters of passive design, used the principle in reverse to create ice by having the wall cast a shadow across a canal running in an east-west direction. This ensured that any ice which formed due to the low air temperature and radiative cooling at night would not be melted by the sun [1]. The solar microclimate therefore is that which happens when the exposure due to radiation from the sun and sky differs from what would otherwise occur. In practice this means that any surface which is not simply horizontal-planar has its own solar microclimate. The nature of the solar microclimate will depend on: the shapes of the surfaces and their surroundings; the reflective, absorptive and emissive properties of the surfaces; and, the quantity and character of the radiation from the sun and sky that ‘illuminates’ the scene.

Irradiance is a radiometric quantity which is equal to the incident total radiant energy (Wm^{-2}). Illuminance is the visible part and it has units of lumens per square metre or lux. The illuminance is equivalent to the irradiance where the power at each wavelength is weighted according to the luminosity function, a standardised model of human visual brightness perception. In this chapter the examples given will show either radiometric (e.g. irradiance) or visible (e.g. illuminance) units depending on the application. It should be noted however that the radiation model used in the simulations does not account for the emission and/or re-radiation of long-wave radiation. Whilst the output of the daylight sources is specified in radiometric units, the reflection models used in the simulation are characterised primarily in terms of visible radiation, e.g. 0.2 or 20% reflectivity for typical ground surfaces. This is a reasonable approximation to employ for many scenarios, however the reader needs to be aware of this limitation when extrapolating to other situations where the quantity and character of the thermal radiation is a key consideration.

2.2 The urban solar microclimate

The interaction between buildings and light from the sun and sky is the defining characteristic of the urban environment. The urban form, in particular its vertical extent, serves to amplify the dynamic character of daylight through the casting and progression of shadows by tall buildings. Planners and architects have long appreciated, at least qualitatively, that the perception of the urban environment is directly related to the prevailing daylight conditions, or as it is often called, the ‘urban solar microclimate’ (USM). A characteristic

feature of urban environments are the large gradients in solar access over small spatial scales. A few stories below an office or apartment perceived as brightly daylight may be one that is quite shaded. Until recently daylight in buildings was thought of primarily in terms of its amenity value. Towards the end of 1990s, the daylighting of buildings began to achieve greater attention for a number of reasons. The two most important drivers were:

1. the widespread belief that the potential to save energy through effective daylighting was greatly under-exploited; and,
2. the emergence of data suggesting that daylight exposure has many positive productivity, health and well-being outcomes for building occupants.

These first of these concerns originated in the 1970s following the energy crisis, and culminated with the widely-accepted need to reduce carbon emissions from buildings in order to minimise the anticipated degree of anthropogenic climate change. This in turn led in the 1990s to the formulation of guides and recommendations to encourage the design and construction of low energy buildings and also for the retrofit of existing buildings. More recently, it is envisaged that buildings could become net producers of energy where there is the potential to deploy electricity generating facades, i.e. building integrated photovoltaic (or BIPV) panels [2].

2.3 The USM and human experience

People will inevitably form judgements about their immediate environment, be it the workplace, home or a public area. Commonly perceived notions of the local solar micro-climate might include the following considerations/appreciations:

- In terms of overall perception, is the space “bright and open” or “gloomy and dark” – this could apply equally to inside and outside spaces.
- Is there direct exposure to sunlight, and if so when and for how long?
- Availability of daylight – how “much” of the sky is visible? Is there a greater “view” of sky for some directions than others?

The primary concern in the daylighting of buildings has generally been to provide illumination for task, e.g. 500 lux on the horizontal work plane. However in the last few decades there has been a gradual increase in awareness of the non-visual effects of daylight/light received by the eye [3]. It is well known that building occupants almost without exception will prefer a workstation with a view of the outdoor environment to a windowless office [4]. A view to the outside indicates of course the presence of daylight, although the relation between view and daylight provision is not straightforward being dependent on many factors. Might there be productivity and well-being benefits in providing building occupants with well daylit spaces? In addition to subjective preferences for daylit spaces, it is now firmly established that light has measurable biochemical effects on the human body, in particular with respect to maintaining a healthy sleep - wake cycle. Could the quality and nature of the internal daylit environment have a significant effect on the health of the human body which can proven through the measurement of, say, hormone levels? Evidence is suggestive of links between daylight exposure and both health and productivity

The urban solar microclimate (USM) therefore has considerations that now extend far beyond the notions of ‘solar access’ that were common in architectural circles a few decades ago.

2.4 The USM in guidelines and recommendations

Efforts to systematise the various perceptions of the USM into a schema that can be applied to the evaluation of building designs or urban plans has not resulted in a consensus view: solar access means different things to different people. Two very different analysis techniques are commonly employed in an attempt to make some measure of solar access in urban environments. One of these is based on shadow patterns cast by the sun at various times of the year, e.g. on the summer solstice. For this, a sequence of images are produced using either scale models with a heliodon or by computer rendering. This approach is essentially qualitative: the brightness of the sun plays no part and the light from the sky is not considered. The other method is based on the illumination provided by a single (i.e. unchanging) standard overcast sky without sun. The brightness of the standard overcast sky increases gradually with altitude from the horizon to the zenith, but it does not vary with azimuth. In other words, the illumination received at any surface will not change if the building model is rotated about the vertical axis. Although quantitative, the second approach is highly idealised because only one sky condition is considered - no account whatsoever is made of the sun or non-overcast skies. It may be that both methods are employed together. However it is not at all clear how, in an analysis, it is possible to weigh one (or more) shadow patterns against a measure of the illumination from a (sunless) overcast sky.

Where attempts have been made to recommend (usually) minimum levels of solar access, the definitions vary and are largely incompatible. For example, in San Jose (USA) solar access is defined as the unobstructed availability of direct sunlight at solar noon on December 21; the winter solstice. Whereas in Boulder (Colorado, USA) an ordinance was enacted to guarantee unobstructed sunlight availability between 10am and 2pm on December 21. These could be tested using the shadow pattern technique. Other definitions make a less specific measure of solar access, e.g. the Solar Envelope [5].

The current situation with the evaluation of solar access has arisen because the fundamentals of the two most commonly used approaches have changed little over the past fifty years. Indeed, they are now part of the mental landscape of the majority of practitioners and researchers, be they planners, architects or engineers. Computer modelling may be used nowadays in preference to scale models to generate shadow patterns and predict illuminance under standard overcast sky conditions. This however gives only the illusion of progress because the fundamental limitations are an intrinsic part of the methodology, not the means by which it is carried out.

The reality of our everyday experience of the daylit luminous environment differs markedly from what the two most commonly used assessment methods can tell us. Light from the sun and the sky (overcast, clear, etc.), both directly and indirectly, illuminates the urban environment. And, of course, the sun and sky act together to provide illumination. Direct sunlight accounts, overall, for about half of the available daylight energy. The remainder comes from the sky and is usually referred to as diffuse light. Of the diffuse (sky) light, less than half of that, depending on locale, is due to conditions that approximate standard overcast. It is evident therefore that the shadow casting and overcast sky methods, either independently or together, provide only a very limited insight into solar

access. To advance our perception of solar access, indeed to make some measure of it that is closer to our experience of the daylit environment, we need to first examine the underlying meteorological conditions.

2.5 ‘Real’ climate

The quantity and character of light from the sun and sky is subject to regular daily and seasonal patterns of variation together with irregular events governed by local meteorological conditions. An illustration of the dynamic nature of sky and sun conditions is given in Figure 1. Hourly values of diffuse horizontal illuminance and direct normal illuminance over a period of a full year are shown as (tiny) shaded rectangles arranged in a 365 (days of the year) by 24 (hours of the day) matrix. The diffuse horizontal illuminance is the visible part of the energy from the sky that is incident on an unobstructed horizontal surface. The direct normal illuminance is the visible part of the energy from the sun and circumsolar region incident on a surface that is normal to the direction of the sun. The shading in Figure 1 represents the magnitude of the illuminance with zero values shaded light-grey. Presented in this way it is easy to appreciate both the prevailing patterns in either quantity and their short-term variability. Most obvious are the daily/seasonal patterns for both illuminances: short periods of daylight in the winter months, longer in summer. The hour-by-hour variation in the direct normal illuminance is clearly visible, though it is also present to a lesser degree in the diffuse horizontal illuminance (i.e. from the sky). Of course, both diffuse and direct illuminance will, in reality, vary over periods shorter than an hour. The hourly datasets however are the most generally available and they do exhibit much of the variation in conditions that might be expected, e.g. in the absolute magnitudes of the two quantities, the occurring sun positions, etc. Furthermore, these standard datasets provide definitive yardstick quantities for modelling purposes.

Figure 1: Illuminance data from a standardised climate file for Nottingham, UK

It is a relatively straightforward matter to generate sky and sun conditions from, respectively, the diffuse horizontal and the direct normal irradiance quantities [6]. It

is understood that it is impossible to recreate an actually occurring instantaneous sky brightness pattern from a measurement of diffuse horizontal irradiance because a real sky may often exhibit unique brightness configurations resulting from cloud patterns etc. However, it is possible to achieve reasonable approximations to actually occurring conditions using theoretical sky models that generate idealised sky brightness patterns from the basic irradiance quantities found in climate datasets. The general character of the sky brightness pattern (e.g. overcast, intermediate or clear) can be inferred from the relative values in the diffuse horizontal and the direct normal irradiances, and the sun position is calculated from the ‘time-stamp’.

2.6 Climate-based daylight modelling

The theoretical models and the basic meteorological data (i.e. standardised weather files) exist to generate hour-by-hour descriptions for the sky and sun that are representative of the actually occurring conditions for the majority of locales in the developed world. 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 these standardised annual meteorological datasets. Climate-based modelling delivers predictions of absolute quantities (e.g. illuminance) that are dependent both on the locale (i.e. geographically-specific climate data is used) and the fenestration orientation (i.e. accounting for solar position and variable sky conditions), in addition to the space’s geometry and material properties.

The term climate-based daylight modelling does not yet have a formally accepted definition – it was first coined by Mardaljevic in the title of a paper given at the 2006 CIBSE National Conference [7]. However it is generally taken to mean any evaluation that is founded on the totality (i.e. sun and sky components) of time-series daylight data appropriate to the locale over the course of a full year. In practice, this means sun and sky parameters found in, or derived from, the standard meteorological data files which contain 8,760 hourly values for a full year. Given the self-evident nature of the seasonal pattern in sunlight availability, a function of both the sun position and the seasonal patterns of cloudiness, an evaluation period of twelve months is needed to capture all of the naturally occurring variation in conditions that is represented in the climate dataset. It is also possible to use real-time monitored weather for a given time period, if calibration to actual monitored conditions within a space is desired. Standardised climate datasets are derived from the prevailing conditions measured at the site over a period of years, and they are structured to represent both the averages and the range in variation that typically occurs. Standard climate data for a large number of locales across the world are freely available for download from several websites. One of the most comprehensive repositories is that compiled for use with the EnergyPlus thermal simulation program [8]. This contains freely-available climate data for over 1200 locations world-wide.

There are a number of possible ways to use climate-based daylight modelling [9, 10, 11, 12, 13]. The two principal analysis methods are cumulative and time-series. A cumulative analysis is the prediction of some aggregate measure of daylight (e.g. total annual illuminance) founded on the cumulative luminance effect of (hourly) sky and the sun conditions derived from the climate dataset. It is usually determined over a period of a full year, or on a seasonal or monthly basis, i.e. predicting a cumulative measure for each season or month in turn. Evaluating cumulative measures for periods shorter than one month is not recommended since the output will tend to be more revealing of the unique

pattern in the climate dataset than of ‘typical’ conditions for that period. Time-series analysis involves predicting instantaneous measures (e.g. illuminance) based on each of the hourly (or sub-hourly) values in the annual climate dataset. These predictions are used to evaluate, for example, the overall daylighting potential of the building, the occurrence of excessive illuminances or luminances, as inputs to behavioural models for light switching and/or blinds usage, and the potential of daylight responsive lighting controls to reduce building energy usage. Thus a daylight performance metric would need to be based on a time-series of instantaneously occurring daylight illuminances since these cannot be reliably inferred from cumulative values [14]. As noted, evaluations should span an entire year. Climate-based daylighting modelling can be used in both cumulative and time-series modes to help evaluate and understand the urban solar microclimate, examples for which are given in the following sections.

All the examples shown in this chapter were created using a climate-based daylight modelling (CBDM) tool founded on the *Radiance* lighting simulation system [15]. The CBDM software (created by the Mardaljevic) is a gradually-evolving suite of tools for investigating a wide range of daylighting applications, including non-visual effects [16]. Some of the CBDM modalities described in this chapter are now available in end-user tools such as DAYSIM¹. As noted in Section 2.1, the radiation model used in *Radiance* does not account for the exchange of long-wave radiation.

3 Visualising the urban solar micro-climate

It is proposed that the total annual illuminance (or irradiance) incident on a surface should be used as the basis for visualising the “urban solar microclimate”. As noted above, any cumulative period shorter than a full year will not be representative of the overall prevailing conditions for that locale. A cumulative measure (illuminance or irradiance) over a full year provides a relatively unambiguous basis for the USM. And, since standardised climate data are used, the results offer a “yardstick” for comparison purposes.

3.1 The San Francisco 3D model

One of the first complex scenes to be irradiation mapped was a 3D model of the financial district in San Francisco [17]. At the time this was one of the more complex 3D city models available on the web. A rendering of the model with the texture-mapped surfaces removed is shown in Figure 2. For this rendering, the model was illuminated by three light sources – effectively, three ‘suns’ – to better show detail in the geometry than would be the case with a single light source.

Five views showing the total annual irradiation (TAI) incident on the surfaces of the San Francisco city model are given in Figure 3. The central image shows the TAI as viewed from directly above an area in the centre of the model. The magnitude of the predicted TAI is shown using false-colour – the legend indicates the range used for the mapping, i.e. 200 kWh/m² to 1400 kWh/m². The surrounding images show the views from the four mid-compass directions, e.g. north-east, south-east, etc. Most readily apparent is the difference in the total annual irradiation between the two views from the north and those from the south. On closer inspection, the large gradients in total annual irradiation across many of the building facades becomes evident.

¹<http://daysim.com/>

Figure 2: 3D model of San Francisco

These images are first and foremost representations of quantitative data – the result of exacting computations. Their significance however can be readily appreciated by non-engineers – planners and architects quickly understand the significance of the data. This is in large part because the approach is view-based. Each 600 by 600 pixel image is comparable to a visualisation of the annual total of hourly data collected by 360,000 irradiance meters arranged over the building facades, ground etc. Therein lies one of the key advantages of an image-based approach over a points-based calculation: the new technique makes visible, literally, the solar microclimate in complex urban settings. If desired, the individual pixel values can be read interactively on-screen.

The San Francisco city model was chosen because it was, at the time, one of the most detailed 3D models freely available on the Web. The climate dataset (TMY) for San Francisco was downloaded from the Renewable Resource Data Centre in the US. Hourly sun and sky conditions for San Francisco were derived from the meteorological data and used in the simulations. An unexpected feature of using San Francisco was that the total annual irradiation on unshaded east-facing surfaces was predicted to be a little lower than on unshaded west-facing surfaces. At first this was puzzling because weather files for other locations did not show this effect. Further investigation revealed that this is in fact a consequence of the San Francisco morning fog. The fog occurs so regularly throughout the year that its effect is present in the weather file: irradiation from the sun in the morning (in the east) is slightly attenuated compared to irradiation in the afternoon (in the west) when the fog has usually lifted. It is noteworthy that this subtle aspect of the locale should be discernible in the visualisations of the solar access. The use of the San Francisco model was important also to demonstrate the inherent scalability of the approach: to have real-world application there should not be practical limits on the complexity of the 3D model used in the simulation. The approach shown here can be equally applied to small scale architectural features as to large scale city models.

3.2 Harvesting solar energy

Of the renewable technologies that have been proposed to reduce the carbon emissions associated with the energy consumption of buildings, in-situ generation of electricity by photovoltaics (PVs) is considered one of the most promising [18]. Photovoltaic devices at present are based on silicon in various formulations. New materials and novel approaches to PV fabrication are under vigorous investigation. Whatever the type of the PV mod-

Figure 3: Five views of the San Francisco 3D model showing the predicted total annual irradiation

ule, the potential for exploitation of building integrated photovoltaic (BIPV) installations depends primarily on the available solar irradiation. A report by the UK Department of Trade and Industry gave details of 16 typical BIPV projects [2]. For these demonstration projects – completed, planned or speculative – shading issues were largely avoided by choosing open sites with minimal nearby obstructions. In the medium-to-long-term however, BIPV in dense urban environments will need to be considered since this is where the majority of the energy use takes place. The wider adoption of BIPV will depend on sound demonstrations of its economic viability. Foremost in the evaluation of PV economics is the calculation of the available solar energy. Images of total annual irradiation allow rapid identification of candidate facade and roof areas where the total received solar energy is sufficient to warrant consideration as a site for BIPV. The performance of a BIPV installation can be degraded by transient shading effects which are not revealed in images showing cumulative totals. So detailed analysis of these effects using a time-series might need to be required once a candidate site has been identified.

Another, rather more speculative, technology that has been proposed to harvest solar energy in urban environments is the growth of algae to produce bio-fuels. The key rate-limiting ‘external’ factor for algal growth is the availability of the photosynthetically active component of daylight. In the urban environment, the degree and occurrence of daylight availability results from the complex interaction of the built form and the irradiation micro-climate. Maximum, sustainable yield of biomass from algae photobioreactors (PBRs) would depend on the optical design being tailored to the available light-field [19]. Thus the optical design of the PBRs at small scales would need to be optimised with respect the large-scale urban irradiation microclimate and the surface type used. This is another potential application for multi-scale irradiation mapping: to determine the quan-

tity and distribution of photosynthetically active radiation across all relevant scales from the centimetre dimensions of the transparent tubes of an algae reactor to large-scale 3D city environments.

3.3 A strategic evaluation of urban solar potential

Whatever the nature of a solar technology intended for urban settings, the economic rationale for its wide-scale deployment will depend on an assessment of both the total available facade area and the solar potential since the effectiveness of these technologies is critically dependent on the magnitude of the received total annual irradiation. How this might be achieved in practice is as follows. The building facade area, graded for total annual irradiation, was determined for the entirety of the 3D model shown in Figure 2. To gain further insight into this quantity, a two dimensional grading was used: the facade area was sorted into bands of TAI and height above ground. The results are shown in Table 1. The total area for vertical and slightly sloping facades was determined to be $1.18 \times 10^6 \text{ m}^2$. The target area was set to include the entire model (to remove the need for incremental steps) and five views similar to those shown in Figure 3 were generated. The irradiation map for one view is given in Figure 4, with one of the height ranges shaded green for illustration.

Figure 4: Strategic evaluation of solar potential for the San Francisco 3D model

The *Radiance* software on which the CBDM system is founded uses a backwards ray-tracing method to transport light. Compared to say radiosity, ray-tracing in *Radiance* places few, if any, limitations on either material properties (for both transmission and reflection) or scene complexity. However, a consequence of the ray-tracing approach is that the solution for global illumination is not ‘coupled’ to the scene geometry. In other words, the full solution is obtained only for those surfaces that are visible in the image. Thus, in order for a survey of the 3D model to be comprehensive, multiple views from several vantage points must be taken to ensure that most of the building surfaces are visible in at least one of the images - hence the high-up viewpoint for the image shown

in Figure 4. Using tools that are part of the standard *Radiance* release it is possible, for every pixel point in an image, to determine the following:

- the solid angle subtended by the pixel;
- the surface normal at the point where the ray intersects the model; and,
- the world (i.e. x, y, z) co-ordinates of the point of intersection.

From these data it is then a straightforward matter to determine the (building) surface area associated with each pixel – for which, of course, there is a prediction of total annual irradiance. Then, in summing – and grading – the building surfaces over the five images, it is necessary to avoid the multiple counting of building surfaces since they are usually visible in more than one image. For most vertical surfaces, the azimuth of the surface normal is a sufficient discriminator to avoid multiple counting. The method therefore provides an estimate of TAI graded surface area rather an exact solution. Tests have shown however that for many typical geometries the approach delivers results of more than acceptable accuracy. Furthermore, data on this scale and resolution would be otherwise unobtainable with such relative ease.

Height range [m]	Total annual irradiation (Wh/m ²)			
	4E5 to 6E5	6E5 to 8E5	8E5 to 1E6	>1E6
3 to 25	1.04E+05	4.96E+04	3.73E+04	1.92E+04
25 to 50	1.03E+05	7.68E+04	4.78E+04	1.66E+04
50 to 75	6.96E+04	9.08E+04	5.71E+04	1.68E+04
75 to 100	3.54E+04	6.91E+04	6.31E+04	1.64E+04
100 to 125	1.85E+04	3.86E+04	4.94E+04	1.84E+04
125 to 150	7.47E+03	2.51E+04	3.52E+04	2.17E+04
150 to 175	6.44E+03	1.44E+04	2.11E+04	1.74E+04
175 to 200	2.68E+03	3.82E+03	6.80E+03	4.08E+03
>200m	2.13E+03	3.36E+03	7.01E+03	3.17E+03

Table 1: Facade area (m²) graded for total annual irradiation and height above ground level for the San Francisco model (see Figure 4).

3.4 Irradiation mapping of ‘virtual London’

The 3D model of ‘Virtual London’ shown in Figure 5a (without textures) comprised approximately 340,000 polygons. As can be seen in the rendering, the buildings are mostly flat-topped. For the determination of total annual irradiation received at the ground, having flat-topped rather than pitched roofs should not greatly influence the outcome. The image below the rendering shows a prediction of total annual irradiation - as ‘seen’ from above - across an area approximately 12 km² (3km×4km), Figure 5b. The irradiation map is superposed on a satellite image of a wider area. The reflectance of the building surfaces was set to 0.2. The total annual irradiation received for an unobstructed horizontal surface is approximately 1,000 kWhm⁻² (yellow in the colour plates). The irradiation map dramatically reveals the effect of urban texture - the greater the building density, the lower the cumulative irradiation which reaches the ground. In the ‘canyons’

between tall building the total annual irradiation is of the order of 50 kWhm^{-2} or less (blue in the colour plates).

Government agencies have responded to calls from various quarters to promote ‘green’ spaces in cities. The amenity aspects of green spaces are usually foremost in these discussions, however there are now recognised positive health and well-being aspects also [20]. In dense urban environments, the key consideration is the availability of daylight to support plant growth and survival. Plant species for shaded ‘green’ areas should be selected on the basis of the predicted levels of the photosynthetic component of total annual irradiation. Here perhaps knowledge of the seasonal components would be helpful too. Assessments of the available area and prevailing illumination for planting could be carried out at a city wide scale using images such as the irradiation map shown in Figure 5b. Instead of total annual irradiation, the legend could be shown in units of photosynthetic active radiation [21], or, more simply, something that relates to everyday notions of overall shade, e.g. a ‘half’ or ‘quarter’ shade. To help planners, the irradiation map images could be incorporated as a layer in a geographic information system (GIS) [22].

The low cumulative irradiances predicted at ground levels are an indication of the potential for the ‘urban texture’ to ‘trap’ radiation and so add to the urban heat island (UHI) effect [23]. The irradiation map therefore may have some role as a proxy for radiation trapping if it can be shown that there is a robust relation between the cumulative irradiation at ground level and the radiation absorbed by (largely vertical) building surfaces.

4 The ASL building: A solar access study

This section describes a solar access study carried out for a building in New York (USA) where a proposed development has the potential to significantly reduce the daylight availability for the existing building. The building at risk of daylight injury from the proposed development is the historic Art Students League. The evaluation proved to be a landmark study – we believe that it is the first example in any city where the legal agreement covering the development of a site incorporates measures of daylight availability founded on climate-based daylight modelling.

4.1 Density and zoning in New York City

Density in New York City is governed by the New York City Zoning Resolution which primarily uses the concept of Floor Area Ratios to regulate building size. In much of Manhattan maximum building height is not directly regulated, but the amount of floor area allowed is limited to a ratio of zoning floor area to lot area.² The maximum Floor Area Ratio (FAR) for a new residential building in Manhattan in its highest density district is 12 FAR with standard density bonuses (or 12 feet of building area for every one foot of lot area). For commercial buildings the maximum is 18 FAR with all standard bonuses.

Yet, very large buildings have recently been built legally under the New York City Zoning Resolution that obviously appear to have FARs much larger than the maximums allowed under the Zoning Resolution. In most of these cases these large buildings are

²Zoning floor area is similar to building floor area, but does not include cellars, pipe chases, mechanical spaces, certain accessory parking, and some other typically small areas of buildings.

Figure 5: Map showing the predicted total annual irradiation for central London overlaid on aerial photograph

allowed because the Zoning Resolution also allows something known as a Zoning Lot Merger (ZLM). A ZLM is a legal agreement between separate land owners which merges adjacent tax lots so that they are considered as a single larger lot for the purposes of zoning.³ This mechanism allows owners of buildings that are smaller than what the underlying zoning allows to sell their unused floor area to adjacent developers while still owning and operating their building. ZLMs allow developers to build very large buildings that would not be allowed under zoning if the maximum FAR was calculated only on the property owned by the developer. A ZLM is commonly referred to as selling “air-rights”, but is actually more than just a transaction involving floor area, as all other zoning rules apply to this larger lot including lot coverage, building spacing and legal windows. So, for example, a building on a merged zoning lot may be able to have windows allowing legally habitable rooms on a lot line.

³The mechanism is described in Section 12-10 of the New York City Zoning Resolution [24].

4.2 The Art Students League building

The Art Students League of New York (ASL) is housed in a 4-story brick and limestone building on West 57th Street in Midtown Manhattan. The building is both historically and architecturally notable and has been designated a New York City Landmark, which means that no changes to the structure that are visible from the street would be allowed without the approval of the New York City Landmarks Commission. The institution has educated many notable artists and remains a magnet for talent from around the world. This talent was educated, in part, in two artist studios that occupy the top floor of the building. These artist studios have no artificial lights and are lit by north facing skylights.

A new development was proposed on the lot adjacent to the ASL by the Extell Development Corporation, which is the developer of some of Manhattans largest new buildings. A very tall building on the site would have largely clear views of Central Park, the southern boundary of which is just two blocks to the north. Views of Central Park are considered a desirable amenity for luxury residential units and the taller the building, the more units would have views of the Park, which provided incentive for Extell to merge lots with the ASL. Both lots are split between the C5-1 and C5-3 zoning districts. C5-3 is one of the highest density districts in Manhattan, with FARs up to 18 with density bonuses. The C5-1 district is high density with a maximum FAR of 10. The existing ASL building is 33,979 ft² (3,156m²), and its lot is 15,062 ft² (1,399 m²) which meant that it had 154,296 ft² (14,334 m²) of unused floor area that it could sell to Extell for use in the building planned adjacent to it. Further, a merger with the ASL would allow the proposed building to have legal windows along the lot line.⁴ Finally, if the ASL merged lots with Extell, it would mean that other lots to the east of it on the same block could be merged with the Extell lot providing the proposed building even more floor area.

If the Art Students League sold the development rights and a large building was constructed so close to the skylights, the amount and quality of daylight to the artist studios could be degraded. Before any final decisions regarding the sale of the floor area to Extell, the ASL needed to know how much their skylights could be affected, how building design would impact the light the skylights received, and finally, if the amount of diminution was large, what kind of remedy, if any, would be available.

4.3 Quantifying the potential daylight injury

The challenges for the evaluation of potential injury were as follows:

1. To determine some meaningful measure of the reduction in daylight levels caused by the proposed building.
2. To quantify the sensitivity of the injury to various design alternatives.
3. To 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 deemed either inappropriate or could not address fully their concerns. For example, the skylights are north facing and receive hardly any direct sun, so the offered shadow pattern study was 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 already appreciated how the character

⁴This expression refers to windows that can make a legally habitable room.

of illumination in the ASL studios depends on the various sky conditions, including the potential for reflected sunlight from nearby buildings – aspects of natural illumination that the daylight factor approach cannot address.

Figure 6: Art Students League Building (right) with adjacent lot

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. In everyday terms, this is equivalent to the cumulative measure of illumination recorded by a light meter left at a fixed position on a building for a full year. The potential daylight injury to the studios would be determined by predicting the total annual illuminance incident on the skylights for the existing situation and with the proposed building in place. For the client, the significance of these measures was readily understood since a decrease in incident illumination at these skylights translates directly into reduced daylight provision for the studios.

Standard climate datasets contain hourly values for various irradiation and illumination quantities (Section 2.5). From these it is possible to derive hourly-varying sky and sun conditions for use in lighting simulations. Equally, it is possible to synthesise 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 configurations. Separate luminance maps for the annual cumulative sun and the annual cumulative sky were synthesised from the standard climate TMY2 dataset for New York City (WBAN# 94728).

A highly detailed 3D model of the ASL and surrounding buildings was employed in the simulations. Renderings of the 3D model showing both the existing situation and with the proposed development are given in Figure 7. The two skylights – the only sources of daylight for the studios – are enclosed by the dashed-line-ovals. Note that the skylights are not the same size. The 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 and with the proposed tower in place (Figure 7). Simulations with the proposed tower in place were

carried out with the tower reflectivity set first to zero and then 50%. The zero reflectance case determines the diminution of TAIL with the tower acting purely as an obstruction. For the 50% reflectance case, the tower acts both as an obstruction and a reflector of light from the sun and the sky, including multiple reflections from other buildings. 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 then be determined from a simple interpolation of the results for the zero and 50% reflectivity cases. A summary of the results are presented in Figure 8. In addition to the mean TAIL for each skylight marked on the images, the inset value shows the area-weighted mean TAIL for the two skylights.

The area-weighted mean TAILs were 36,946 klux hours for the existing scenario, 23,455 klux hours with a tower of zero reflectance and 29,972 klux hours for a tower with 50% reflectance. The results are summarised in Table 2. The simulations showed that the building as planned had a potential to significantly impact the quantity of natural light that reached the skylights of the artist studios. The simulations also showed that the impacts on the skylights could be mitigated through both building design and materials.

Figure 7: Existing and proposed arrangement of buildings - skylights marked in blue and ringed

Case	Predicted TAIL [klux hrs]	Change in TAIL [%]
Existing	36,946	
Proposed 0% refl.	23,455	-36.5%
Proposed 50% refl.	29,972	-18.9%

Table 2: Predicted change in total annual illuminance (TAIL) caused by the proposed building

Figure 8: Total annual illumination incident at the skylights for the existing and proposed cases

4.4 Outcomes and implications

The information from the simulations was used in at least two ways. First, and most importantly, they showed the ASL management that there was real risk to the amount and quality of the light reaching their artist studios. In other words, unlike most Zoning Lot Mergers where the seller has little risk of impairing their property, the ASL faced a very real risk of a diminution of an important asset. Knowing these risks, the ASL was more informed during negotiations with Extell regarding the Zoning Lot Merger. Second, the simulations helped to guide the legal agreement for the Zoning Lot Merger that came out of the negotiations. Extell has agreed to attempt to minimise the impact their building will have on the skylights to the greatest degree possible, provided the developer is still able to use all the floor area he has acquired. Extell has further agreed to provide the ASL plans for the proposed building early in the design process so that the ASL can evaluate the buildings impact and suggest ways an alternate building design could mitigate impacts. The developer has reserved the right to build a building that may seriously impair the light received by the skylights, but this would require a one-time payment of \$10,000,000 to the ASL for damages.

While not entirely novel – some of the same techniques were applied in the New York Times evaluation (see Section 5) – the nature of this study was certainly unusual for New York City. Codified in the City’s environmental reviews are requirements for shadow studies, but except in very limited circumstances, proposed projects are not required to study impacts on daylight, on either public or private property. This is ironic considering that one of the major reasons for the adoption of the nation’s first zoning ordinance, the 1916 New York City Zoning Resolution, was because very large buildings (such as the famous 31-story Equitable Building) were built with no setback from the sidewalk and created very dark streets. The darkness these buildings created was only partly related to the shadows they cast, of course, and have much more to do with the amount of sky that is visible from the street. The New York City Zoning Resolution recognises that the sky is important to creating light and attractive streets, and requires in many zoning districts sky exposure planes to ensure that light reaches the street below. Indeed, the Mid-town Special District adopted in 1982 includes a performance-based sky exposure system based on the Waldram diagram that helps to shape the building form to maximise sky-exposure from street level. Nevertheless, despite these relatively innovative regulations to increase the exposure to sky that are already part of New York City’s law, developers are never required to measure their proposed project’s impact on light.

The ASL study helps to show both how simple and how important it can be to study

the impact of a proposed building on neighbouring buildings and at the street/sidewalk level, and that simulation can be used to inform design and minimise impacts. Considering the state of the current practice, the time may be coming when instead of simply following a predetermined sky exposure plane that may or may not impact light reaching the street, a designer can demonstrate how a proposed building will actually diminishes light levels at the street. Such concepts shouldn't be revolutionary, yet when they regard regulations that are slow to change, they often are.

The ASL study also has implications for the UK where the almost century-old “rights to light” schema devised by Waldram [25] for the determination of daylight injury has recently been critiqued in a number of papers [26, 27, 28, 29]. The measure of daylight used in the Waldram method is direct sky illumination under a uniform sky (without sun). It is now believed that this measure has little correspondence to commonly perceived notions of daylight sufficiency. Furthermore, the measure is largely irrelevant for the purpose of, say, determining the injury (i.e. degraded performance) of some solar-dependent building technology, e.g. BIPV. Indeed, for photovoltaics a decrease in total annual illuminance (or alternatively, irradiance) has direct correspondence to the degradation in performance caused by the introduced over-shadowing. Thus, the analysis described for the ASL building could, with minimal adjustment, quantify the reduced output of a BIPV array, and so provide a basis for financial compensation to indemnify the owner for the reduced performance of the system. BIPV installations are costed on a performance life-time of 20 years or more, during which time it is quite probable that an unforeseen building development could be proposed that over-shadows the BIPV array to some degree. As yet there is no technical-legal framework to assess the degree of injury. Climate-based daylight modelling however, using standardised climate files, is well suited to provide the technical basis for any legal procedure(s).

The financial injury due to overshadowing on a BIPV array is a relatively straightforward quantity to estimate. Putting a price on injury due to reduced solar access at a window however is considerably more problematic because, unlike electricity, units of daylight (e.g. the lux-hour) do not have a tangible monetary value. In part, this is because effective daylighting for buildings needs artificial lighting controls that respond to varying levels of daylight illumination. Field-trials in San Francisco have shown that daylight responsive lighting control systems can “bring about sustainable reductions 30 to 41% in electrical energy for an outermost row of lights in a perimeter zone, and 16 to 22% for the second row of lights” [30]. The field trials should to be repeated for other settings and locales. However, it is clear that there is considerable potential to reduce electricity demand for lighting. Thus it should be possible to place a monetary value on daylight. However, solar gain and the resulting cooling should also figure in the estimation of overall energy consumption. It may be that additional overshadowing could reduce the energy consumption of the ‘injured’ building if the reduction in cooling exceeds the increase in electric lighting consumption. These interactions are complex, however it is conceivable that the irradiation mapping technique could be expanded to include some representation of the energy flows across the building perimeter. Then it would be possible to carry out fairly detailed energy modelling of the facade and perimeter zone of the building using only the building envelope and a ‘virtual construct’ for the internal spaces. Sometimes so much solar radiation is reflected from buildings using mirrored glass that the heat load on adjacent buildings is increased [31]. These and similar effects could in principle be predicted using the irradiation mapping mode of climate-based daylight modelling.

5 Daylighting the New York Times Building

The New York Times (NYT) Building is a 52-story tower on the east side of Eighth Avenue between 40th and 41st Street in the borough of Manhattan. The building, which houses the New York Times Newspaper, was announced at the end of 2001, construction started in 2003 and it was completed in 2007. Daylight simulations were used to support decisions later in the design process during the construction phase of the building, rather than for early schematic design or meriting green building status.

The NYT building features an automated shading system where a motorised roller blind is deployed incrementally according to some sensor input, e.g. measured daylight level. This shading system features in the facade design throughout the majority of the 52 floors of the building [32]. The design goals for the shading system were to:

- maximise natural light;
- maximise occupant connectivity with the outdoors, i.e. external views;
- intercept sunlight penetration so as to avoid direct solar radiation on the occupants;
- maintain a glare free environment; and,
- to provide occupant manual override capability.

The overall intent was to keep the shades up as much of the time as is possible without causing thermal or visual discomfort. Thermal comfort is assured by solar tracking and the geometry of the external sun screens. Visual comfort is attained by managing the luminance on the window wall so that it does not exceed certain threshold values. A manual override system was specified because previous post occupancy evaluations of automated shade systems indicated that occupants were likely to complain if a manual override was not provided. Although a formal post-occupancy evaluation of the New York Times Building has yet to be carried out, anecdotal evidence from informal surveys indicates a high level of user satisfaction with the daylighting systems. Furthermore, effective daylighting has significantly reduced the energy consumed for artificial lighting. The NYT daylighting system provides a degree of modulation for the shading (they are deployed by increments) and has greatly reduced the need for user interventions. Good daylighting alone is unlikely to save energy unless it is part of an integrated design scheme. The typical lighting power densities (LPDs) for consumed electricity in office spaces range from about 12 to 20 Wm^{-2} , with those at the lower end considered ‘good practice’. It is possible however to achieve LPDs significantly lower than the good practice value – without recourse to emerging technologies such as light emitting diodes – using only good quality low-energy fluorescent lights. This was successfully demonstrated in the New York Times Building which has a LPD of only 4.26 Wm^{-2} . The simulations that were carried out in support of the design and calibration of daylighting systems of the NYT building are described in the following sections.

5.1 3D model for NYT building and surroundings

Extensive *Radiance* simulations were used to assist the building owner and manufacturers in making informed decisions on the design and control of an automated roller shade and electric lighting control system for The New York Times Headquarters in the pre- and post-bid phases of the project [32]. A prior monitored field study in a full-scale mockup

answered initial questions concerning technical feasibility and performance benefits of automated control. Simulations enabled extension of the monitored field study to the final building in its complex urban context. The 3D model created for the NYT building was highly detailed since the daylighting properties of the spaces in the tower are dependent on both the small-scale facade structures (e.g. the ceramic bars) and of course also the properties of the space (e.g. desk layout, partition height, etc.). The detail achieved can be seen in the ‘close-up’ image of the NYT tower in Figure 9. The office detail was generated and ‘inserted’ into the building envelope model at the appropriate floor level for the daylighting simulations. The facade detail for the levels above and below the floor was also added since these could affect the ingress of daylight to the space. Note that realistic finishes were applied to all internal and facade surfaces for the NYT office model, e.g. desktops, furniture, floor, etc. (see x100 rendering). The 3D model for the tower with office detail for one floor comprised about 200,000 polygons.

The NYT tower was set in a 3D model of Manhattan of extent approximately 3km by 2km. This surrounding context comprised nearly 300,000 polygons. Thus the tower and context model in total comprised nearly half a million polygons (Figure 9). Most of the context building surfaces were given a default diffuse reflectance of 0.2, which is typical for many buildings. However, certain context buildings near to the NYT tower were assigned more specific reflective properties, including part specular, based on observations of the building. One of the key daylighting parameters to be investigated was visual comfort for the building occupants. Thus the luminance of the view to the outside - which may include reflections from surrounding buildings - needed to be accurately captured in the simulations.

Figure 9: Renderings of the NYT building and surrounding context - three views showing effective magnifications of x1, x10 and x100

5.2 The spatio-temporal dynamics of sunlight exposure

Daylight simulations were used for a variety of purposes, from understanding the effects of urban shadow on shade usage to assisting with pre-calibration of photosensor sensitivity in a complex daylit interior environment. Time-lapsed images enabled stakeholders (building owner and manufacturers) to visualise the daylit environment of the final building in its urban context with automated shade control and assess how well visual comfort (direct sun, surface luminance), daylight quality (illuminance level and distribution), and view were to be addressed by the system at different orientations and locations within the building.

The spatio-temporal dynamics of direct sun illumination were investigated using a combination of spatial exposure maps and temporal exposure maps. The spatial exposure

map shows the cumulative number of hours of sun exposure assuming clear sky conditions throughout the year. Sun exposure maps of the principal building facades reveal the transition from heavily obstructed, through moderate to low/zero obstruction, and so helped to guide the designers in the selection of shade material and zoning of the control system for the automated roller shades.

The spatial exposure map for the south facade of the NYT tower is shown in Figure 10. The exposure in number of hours is shown using colour. The accompanying temporal exposure maps are for two selected points on the building facade and show the propensity for sun exposure throughout the year at a time-step of 15 minutes. The presentation is similar to that used for the climate data given in Figure 1, only now the time-step is shorter. In the temporal map, colour is used to reveal the angle between the facade surface normal and the sun vector. For example, angles of 80° or more are grazing incidence and will have little penetration into the building, whereas angles around 10° or less indicate when the sun vector is almost normal to the facade, i.e. the sun is ‘shining’ almost face-on and will penetrate deeply into the space. The south facade has an orientation that is a little west of south, hence the exposure (and penetration) is greater in the afternoon. Note there is no correction for daylight savings in the temporal maps. Times when the sun is below the horizon (i.e. night-time) are shaded white, when it is above the horizon but ‘behind’ the facade the shade is grey, and when the sun is obstructed by surrounding geometry the shade is black. The temporal maps for points on the 6th and 26th floors of the tower readily show how the propensity for solar exposure varies throughout the year, Figure 10. On floor 26 between the hours of about 13h and 16h during winter, the sun shines almost face-on to the south facade. This presents the greatest risk for visual discomfort for persons on that floor occupying the south perimeter. For floor 6 however, the angle between the sun vector and the facade surface normal is rarely less than 40° , and then only for short periods lasting 15 - 30 minutes around 15h during winter. The ‘spike’ of colour in the temporal map surrounded by black suggests that low winter sun is only very occasionally not obstructed by surrounding buildings.

5.3 Balancing daylight provision and visual comfort

A good provision of daylight is now considered to be highly desirable in terms of building occupants’ well-being and productivity [33][34]. Daylight however can cause visual discomfort by inducing glare and veiling reflections. Efforts to control glare often result in the loss of predicted daylight benefit as occupants deploy blinds etc. which may remain closed long after the glare condition has diminished. Annualised, climate-based daylight simulations were conducted to more thoroughly assess comfort conditions and availability of view for the NYT occupants.

In the CIBSE Lighting Guide LG7 glare is defined as a “Condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or to extreme contrasts.” [35] There are two types of glare: disability glare, where stray light reaching the eye results in a reduction of visibility and visual performance, and discomfort glare, which leads to users’ discomfort, often with less immediately noticeable effects such as headaches or posture related aches after work. Glare can be caused by direct sunlight through a window or by the luminance differences between bright areas such as windows with bright sky views and the darker task area. Furthermore, veiling reflections on reflective surfaces such as computer screens can affect visual comfort at workstations facing away from the window.

Figure 10: Spatial and temporal exposure maps for the NYT building

While there are accepted, albeit imperfect, models for the potential glare effect of (fixed output) luminaires, it is recognised that glare from daylight sources is poorly understood [36]. The first daylight glare formulations were extrapolations from studies of discomfort glare due to artificial lighting [37]. The light sources used in those studies subtended relatively small solid angles from the viewpoint of the subject, and the luminance conditions (source and environment) were very different from typical daylit offices. In short, those extrapolations proved to be inadequate for the purpose of determining discomfort glare from daylight.

For the NYT study the project team made preliminary overtures to derive a visual comfort-based metric similar to the thermal comfort percent people dissatisfied (PPD) metric. In the US, mechanical engineers have long relied on the metrics defined in the ASHRAE Standard 55 [38] to determine whether mechanical system designs will provide thermal environmental conditions acceptable to a majority of the occupants within the space. The predictive model is based on hundreds of field and laboratory studies that correlate physical measures to subjective response. Calculations are done for critical design conditions, that is for the 1% or 3% peak condition, e.g. for high levels of solar radiation that are exceeded for only 1% or 3% of the year. For more innovative designs (naturally ventilated, hybrid ventilation schemes, or large amounts of glazing), more detailed calculations are conducted: e.g., spatial distribution or temporal computations of PPD.

Conversely, predictive models for visual comfort are based on very few, limited field studies and consequently, there are no standards or requirements in place to ensure provision of visual comfort with daylighting designs: the occupant is simply expected to lower the shade. With the increased interest in daylighting and with the use of innovative systems, the need for robust predictive models for discomfort glare, in particular, is acute and was needed particularly for the NYT analysis. A simplified measure was used to evaluate comfort conditions based on a limited field study [39] and on calculations derived from a combination of comfort metrics (luminance ratios, daylight glare index, etc.). The resulting measure was the number of annual hours when the mean window luminance exceeded 2000 cd m^{-2} . This measure helped to determine the tradeoffs between number of hours of glare discomfort versus access to view and daylight. Calculations were made with the occupants' seated field of view located in a worst case position close to the window in a direction normal to the window, Figure 11.

Figure 11: Simulated plan view showing the position and view direction for the twelve ‘window commissioning’ viewpoints, i.e. wc01 to wc12

Example output for the view position wc04 (i.e. east-facing) are shown in Figure 12. The large plot shows the annual occurrence of predicted mean field-of-view luminance (expressed as hours per day equivalent) for various shade control conditions. The shade control limits were: ‘No shades’ and shades ‘fully down’. The number code (e.g. “99745”) refers to a particular shade material - the analysis was carried out for a number of different shade fabrics. The in-between cases determined the occurrence of mean field-of-view luminance for various control conditions, e.g. blinds were lowered whenever the mean field-of-view luminance exceeded $1 \times 10^3 \text{ cd m}^{-2}$, $2 \times 10^3 \text{ cd m}^{-2}$ and so on up to $5 \times 10^3 \text{ cd m}^{-2}$. At the time of the study there was a ‘rough’ consensus that a mean luminance of 2000 cd m^{-2} can serve as a proxy for visual comfort. From the large plot in Figure 12 it can be seen that (for view wc04) this condition is exceeded on average approximately 8 hours per day with the shades fully up (i.e. ‘No shades’) and for less than approximately 30 minutes

per day with the shades fully down (for material 99745). The small inset rendering shows the simulated view of the sky (black) and neighbouring buildings. The illuminance profiles show the annual occurrence of illuminance at the work plane (also expressed as hours per day equivalent) for the various shade control conditions. For example, with the shades fully down throughout the year, an illuminance of 200 lux is achieved on average only for about 1 hour per day at station 4 (nearest the window) and hardly at all for the other stations. Conversely, with the shades always up, 200 lux is achieved on average for 11 hours per day (station 4) and approximately 5 hours per day at station 1 (furthest from the window). The illuminance profiles for the various shade control conditions can be read from the individual plots.

Figure 12: Annualised profiles for field-of-view luminance (floor 26, wc04) and illuminance at the work station.

The simulations carried out for the New York Times study were used to inform and support the decisions taken by the design team rather than to demonstrate, say, compliance with any current or proposed daylighting metric. It remains to be seen how the recently proposed climate-based metrics will influence the nature and practice of building design and evaluation [14].

6 Summary

The notion of ‘solar architecture’ has existed since the dawn of architecture itself. In 400BC, Socrates is believed to have considered solar design principles in house construction [40]. Until recently the availability of daylight in buildings was thought of largely in terms of task illuminance and the potential to reduce energy for artificial lighting. In the last decade we have discovered that the non-visual effects of light received at the eye can have significant influences on long-term health, well-being and productivity. Furthermore, the imperative to save energy has led to speculation that future buildings could become

‘harvesters’ of energy. All of these factors must lead us to a wider and more rigorous consideration of daylight in the urban setting - in terms of availability to building occupants; the building itself; and also, the public spaces between buildings. The examples given in this chapter show how important it is to accommodate in the simulations building detail across a range of scales, e.g. from shading bars on the facade to the massing of surrounding buildings. Multi-scale climate-based daylight modelling is one of the tools that can help us to understand the complex daylit environment that exists in dense urban environments, giving us the means to maximise the potential benefits of natural light for both buildings and people.

7 Acknowledgements

Simon Gibson (Dept. of Computer Science, University of Manchester, UK) carried out the conversion of the VRML models to *Radiance* format. The San Francisco VRML model was created by Planet 9 Studios, San Francisco, USA. The 3D of ‘virtual London’ was supplied by Infoterra (UK). Eleanor Lee (Lawrence Berkeley National Laboratory, Berkeley, USA) provided material for the section on the New York Times Building.

References

- [1] R. Rael. *Earth Architecture*. Princeton Architectural Press, 2008.
- [2] DTI. Photovoltaics in Buildings: BIPV Projects Programme - Strategy Document 1998-2002. Technical report, Dept. of Trade and Industry, 2000.
- [3] Ann R. Webb. Considerations for lighting in the built environment: Non-visual effects of light. *Energy and Buildings*, 38(7):721–727, 2006.
- [4] Belinda L. Collins. Review of the psychological reaction to windows. *Lighting Research and Technology*, 8(2):80–88, 1976.
- [5] R. Knowles. *Sun, Rhythm, Form*. MIT Press, 1985.
- [6] J. Mardaljevic. Sky model blends for predicting internal illuminance: a comparison founded on the BRE-IDMP dataset. *Journal of Building Performance Simulation*, 1(3):163–173, 2008.
- [7] J. Mardaljevic. Examples of climate-based daylight modelling. *CIBSE National Conference 2006: Engineering the Future, 21-22 March, Oval Cricket Ground, London, UK*, 2006.
- [8] D. B. Crawley, L. K. Lawrie, F. C. Winkelmann, W. F. Buhl, Y. J. Huang, C. O. Pedersen, R. K. Strand, R. J. Liesen, Daniel E. Fisher, M. J. Witte, and J. Glazer. EnergyPlus: creating a new-generation building energy simulation program. *Energy and Buildings*, 33(4):319–331, 2001.
- [9] J. Mardaljevic. Time to see the light. *Building Services Journal*, September:59–62, 2006.

- [10] J. Mardaljevic. Simulation of annual daylighting profiles for internal illuminance. *Lighting Research and Technology*, 32(3):111–118, 1 2000.
- [11] C. F. Reinhart and S. Herkel. The simulation of annual daylight illuminance distributions – a state-of-the-art comparison of six RADIANCE-based methods. *Energy and Buildings*, 32(2):167–187, 2000.
- [12] A. Nabil and J. Mardaljevic. Useful daylight illuminances: A replacement for daylight factors. *Energy and Buildings*, 38(7):905–913, 2006.
- [13] C. F. Reinhart, J. Mardaljevic, and Z. Rogers. Dynamic daylight performance metrics for sustainable building design. *Leukos*, 3(1):7–31, 2006.
- [14] J Mardaljevic, L Hescong, and E Lee. Daylight metrics and energy savings. *Lighting Research and Technology*, 41(3):261–283, 2009.
- [15] G. Ward Larson and R. Shakespeare. *Rendering with Radiance: The Art and Science of Lighting Visualization*. San Francisco: Morgan Kaufmann, 1998.
- [16] J. Mardaljevic, M. Andersen, N. Roy, and J. Christoffersen. Daylighting metrics for residential buildings. *CIE 27th Session, Sun City, South Africa*, 2011.
- [17] J. Mardaljevic and M. Rylatt. An image-based analysis of solar radiation for urban settings. In *PLEA - Passive and Low Energy Architecture, Cambridge, UK*, pages 442–447, 2000.
- [18] IEA. Photovoltaic power systems programme – strategy document 1998–2002,. Technical report, International Energy Agency, 1998.
- [19] C. U. Ugwu, H. Aoyagi, and H. Uchiyama. Photobioreactors for mass cultivation of algae. *Bioresource Technology*, 99(10):4021–4028, 7 2008.
- [20] Jolanda Maas, Robert A Verheij, Peter P Groenewegen, Sjerp de Vries, and Peter Spreeuwenberg. Green space, urbanity, and health: how strong is the relation? *Journal of Epidemiology and Community Health*, 60(7):587–592, 07 2006.
- [21] I Alados and L. Alados-Arboledas. Direct and diffuse photosynthetically active radiation: measurements and modelling. *Agricultural and Forest Meteorology*, 93(1):27–38, 1999.
- [22] John Mardaljevic and Mark Rylatt. Irradiation mapping of complex urban environments: an image-based approach. *Energy and Buildings*, 35(1):27–35, 1 2003.
- [23] Mike Davies, Philip Steadman, and Tadj Oreszczyn. Strategies for the modification of the urban climate and the consequent impact on building energy use. *Energy Policy*, 36(12):4548–4551, 12 2008.
- [24] Department of City Planning. Zoning Resolution, The City of New York. <http://www.nyc.gov/html/dcp/html/zone/zonetext.shtml>, 2011.
- [25] L Harris. *Anstey’s Rights of Light and How to Deal with Them*. 4th edition, RICS Books, London, 2007.

- [26] P. Chynoweth. Progressing the rights to light debate – part 1: a review of current practice. *Structural Survey*, 22(3):131–137, 2004.
- [27] P. Chynoweth. Progressing the rights to light debate: Part 2: the grumble point revisited. *Structural Survey*, 23(4):251–264, 2005.
- [28] Paul Chynoweth. Progressing the rights to light debate: Part 3: judicial attitudes to current practice. *Structural Survey*, 27(1):7–19, 2009.
- [29] P. Defoe and I. Frame. Was Waldram wrong? *Structural Survey*, 25(2):98–116, 2007.
- [30] F. Rubinstein, J. Jennings, D Avery, and S. Blanc. Preliminary results from an advanced lighting controls testbed. *IESNA Annual Conference, San Antonio, Texas, USA*, 1998.
- [31] G.D. Ander. *Daylighting Performance and Design*. John Wiley & Sons, 2003.
- [32] E. S. Lee, S. E. Selkowitz, G. D. Hughes, R. D. Clear, G. Ward, J. Mardaljevic, J. Lai, M. N. Inanici, and V. Inkarojrit. Daylighting the New York Times headquarters building. *Lawrence Berkeley National Laboratory. Final report LBNL-57602*, 2005.
- [33] S. H. A. Begemann, G. J. van den Beld, and A. D. Tenner. Daylight, artificial light and people in an office environment, overview of visual and biological responses. *International Journal of Industrial Ergonomics*, 20(3):231–239, 1997.
- [34] Anca D. Galasiu and Jennifer A. Veitch. Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review. *Energy and Buildings*, 38(7):728–742, 2006.
- [35] LG7 CIBSE/SLL. Lighting Guide 7: Office lighting. *Chartered Institution of Building Services Engineers, London*, 2005.
- [36] W. K. E. Osterhaus. Discomfort glare assessment and prevention for daylight applications in office environments. *Solar Energy*, 79(2):140–158, 2005.
- [37] P. Chauvel, J. B. Collins, R. Dogniaux, and J. Longmore. Glare from windows: current views of the problem. *Lighting Research and Technology*, 14(1):31–46, 1982.
- [38] ASHRAE. Standard 55: Thermal Environmental Conditions for Human Occupancy. *American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta*, 2004.
- [39] R. D. Clear, V. Inkarojrit, and E. S. Lee. Subject responses to electrochromic windows. *Energy and Buildings*, 38(7):758–779, 2006.
- [40] K. Butti and J. Perlin. *A Golden Thread: 2500 Years of Solar Architecture and Technology*. Van Nostrand Reinhold, 1980.