

# Taking daylight modelling out of the dark ages *by* J. Mardaljevic

A look at three new daylight modelling techniques developed at the Institute of Energy and Sustainable Development, De Montfort University, Leicester, UK.

The modelling of illumination and of solar access/penetration are carried out using very different approaches. Daylight illumination is invariably assessed using the daylight factor method under standard overcast sky conditions. Solar access/penetration is typically evaluated using a series of images showing the pattern of direct sun illumination for certain times of the day or year. Both approaches, each over half a century old, were originally carried out using scale model techniques: in an artificial sky for daylight factors or with a heliodon for solar access/penetration. Although different, they share a common trait: at best they each give only a limited insight into the phenomena they are intended to characterize.

Consider first the daylight factor approach. It is readily apparent that illumination under standard overcast sky conditions presents a special case scenario: even in England we see the sun now and then. Northern European climates approximate to the standard overcast sky model for less than 50% of the actually occurring sky conditions. For sunnier climates the approximation is even less valid. For solar access/penetration, the images show only patterns of illumination relating to the sun position. They can indicate only when illumination of a surface may occur, but it is impossible to quantify the degree of illumination or its occurrence throughout the year.

More recently, computer simulation techniques have been successfully applied to both approaches. Daylight factors can be predicted using lighting simulation programs that accurately model inter-reflection, e.g. *Radiance*. Often the same simulation program can be used to render a sequence of images showing the patterns of direct solar illumination inside and on the facades of buildings. Although computer simulation may offer advantages over scale modelling, the fundamental limitations of the basic approach in each case remains.

Over the past five years, research in lighting simulation at the IESD has focused on developing a set of three simulation-based techniques that each offer a significant advance over the traditional approach. Outline descriptions of each follow.

## Daylight prediction

Hourly internal illuminances at any number of points in a building are predicted for a full year. Meteorological conditions are based on Test Reference Year (TRY) data. The prediction technique is based on a refined Daylight Coefficient formulation where the illumination due to each patch of a discretised sky is predicted first. The Daylight Coefficient is the illuminance from a patch of sky divided by the product of the luminance and solid angle of the patch. It depends on the physical characteristics of the room and the external environment, e.g. room geometry, surface reflectances (diffuse and specular), glazing transmissivity, external obstructions and reflections from them. Once the Daylight Coefficients have been

predicted, it is possible to compute the internal illuminance resulting from any number of arbitrary sky and sun conditions using simple (i.e. fast) matrix calculations. Any sky luminance distribution - sky model generated or measured - can be used without requiring further lighting simulations. Another property of daylight coefficients is that they are invariant to building orientation. Consequently, a single set of daylight coefficients can be used to derive internal illuminances for any combination of building orientation, sky model and TRY (i.e. geographical location). This approach therefore is ideally suited for the compilation of a new generation of design guides which would give the daylighting performance of various generic building (and atria) types, based on hourly illuminance values for a full year of realistic meteorological conditions.

The hourly internal illuminances (365 by 24) predicted for one point in an office space are shown in Figure 1. The seasonal, daily and hourly variations are readily apparent in the plot. Below it is a frequency histogram of the illuminances occurring during working hours. Actually, it is four separate illuminance components that are predicted: direct and indirect sky, and direct and indirect sun. Figure 1 also shows the component internal illuminances - the high total illuminance values in winter were, of course, due to direct sun.

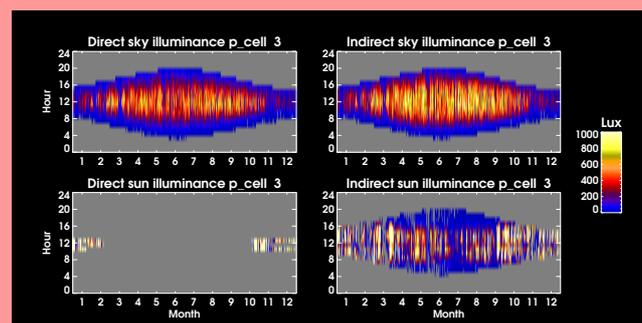
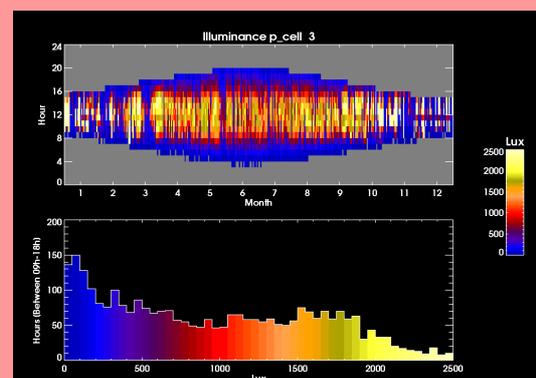


Figure 1

Clearly, this wealth of data needs to be processed and reduced, a task we are currently addressing. Note however that access to the component illuminance data gives a powerful insight into the daylighting of the space. With this data it is possible to quantify the effect of, say, light shelves in terms of shading and redistribution of direct sunlight.

Illuminance predictions from the Daylight Coefficient (DC) formulation have been validated under real sky conditions using the BRE-IDMP dataset. This dataset contains simultaneous measurements of sky luminance patterns, direct normal illuminance and internal illuminance at six points in a full-size office space. There are a total of 754 skies in the validation dataset covering the full range of naturally occurring conditions from heavily overcast to clear. The absolute MBE for the Daylight Coefficient derived illuminances at the six photocells was generally less than 10% and never greater than 13%. The RMSEs were in the range 11% to 19%. This accuracy must be considered as very good in absolute terms, and far better than that demonstrated for scale models under real sky conditions. To date, *Radiance* is the only program to have been validated - for standard illuminance calculation and DC derived illuminances - using measured sky luminance patterns.

## Solar penetration

The total annual irradiation resulting from direct sun incident at the work plane is predicted using an image-based technique. As with the daylight prediction, the sun conditions are derived from hourly TRY data. The total annual irradiation resulting from ~4,400 unique sun conditions is accurately synthesised from less than 200 renderings (the exact number depends on the latitude of the building). The renderings take very little time to compute because inter-reflection is not modelled. Arbitrary floor shapes and complex buildings can be modelled. A total annual irradiation image from a case study example is given in Figure 2.

The building model for this analysis was based directly on the architects' CAD model without any loss of detail. A *Radiance* rendering of the building model used in the simulations is also given in Figure 2. With an image-based approach, comparison of design options is straightforward. For the example shown here, the total annual irradiation was predicted for the building with and without the 'brise soleil'. A difference image, simply the 'without' minus the 'with', revealed exactly the overall effect of the 'brise soleil'. The image data can be reduced to produce plots of the total annual irradiation as a percentage of the work plane area; curves for many design variants can be shown on the same plot. This data can be still further reduced to a single number giving the total (direct) solar energy incident across the entire work plane. Thus not only is the analysis quantitative, but it is also very concise. The same cannot be said of an estimate for shading effectiveness founded on a sequence of images.

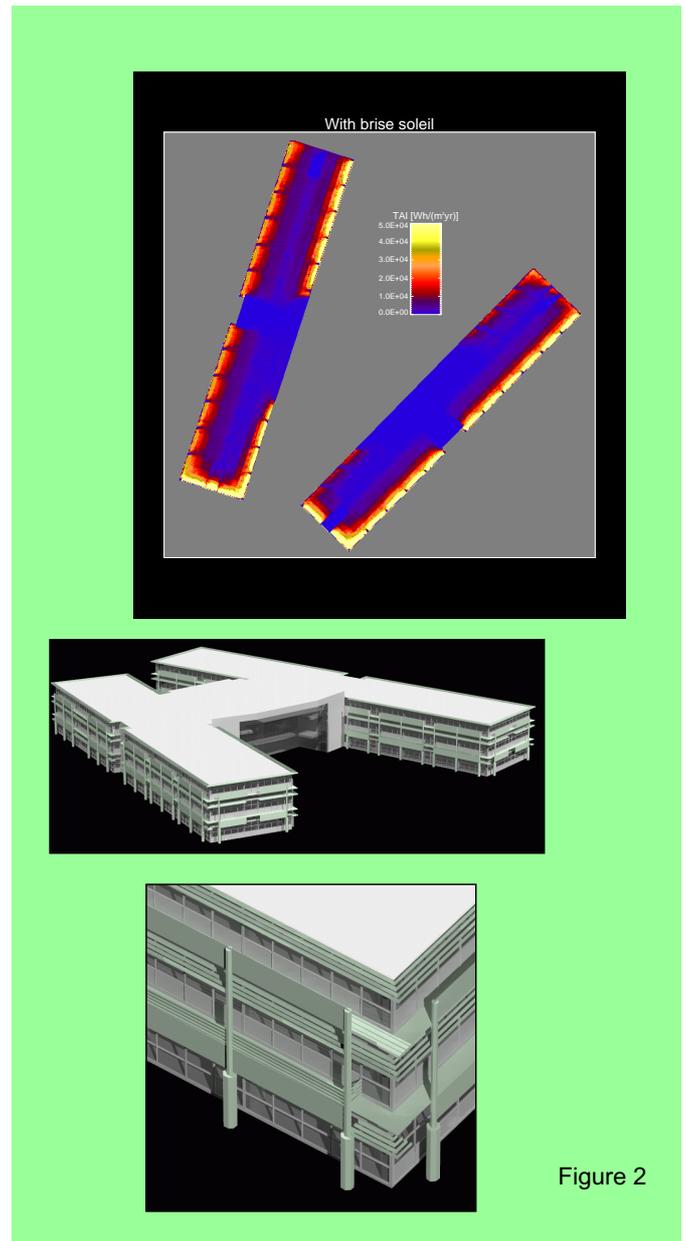


Figure 2

## Solar access

The total annual irradiation incident on building facades is predicted using an image-based technique. Shading and inter-reflection of light between buildings, and diffuse radiation from non-overcast skies are all modelled in the simulation. The annual total is based on the hourly sky and sun conditions derived from a TRY. It is intended that the new approach will be used to map entire city models for available irradiation, as well as for the analysis of specific building designs. An example set of results showing the total annual irradiation for a section of the San Francisco virtual city model is given in Figure 3.

This new technique has a range of applications including: optimal positioning of building integrated photovoltaics (BIPV) in urban environments; the quantification of solar access; the daylight illumination of public spaces between tall buildings. Also, difference mapping can be used to quantify the reduction in solar access (including BIPV efficiency) resulting from a new or proposed building.

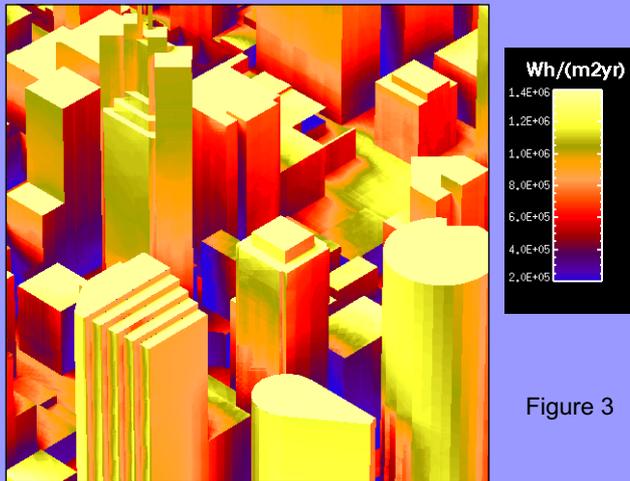
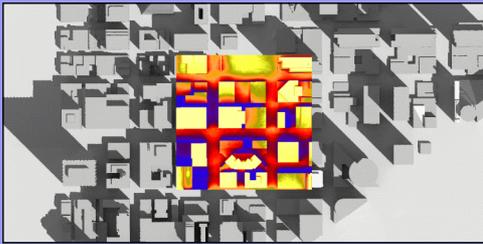


Figure 3

The new techniques described in this article are currently implemented in software on a UNIX workstation as expert-user tools for proof-of-concept, research and demonstration. The tools consist of a suite of numerical analysis and data visualization programs. The tools are entirely command-line driven. There is no 'friendly' Graphical User Interface (GUI) and the simulation parameters etc. need to be coded by hand into the programs. For research, this is not a limitation, it is in fact a necessity. Exploratory investigations require unhindered access to the full functionality of the core simulation engine (i.e. *Radiance*). Something which 'friendly' GUI-based tools invariably prohibit. The procedures to generate the basic data - essentially the rendering processes - are well defined for all three techniques. Some additional work on automation and optimization is required for the formidable task of irradiation mapping entire city models. The processing and reduction of simulation data/images for end-users is an area of ongoing research, particularly for daylight simulation where a vast amount of illuminance data is generated. A specification for end-user versions of the techniques will be defined once these issues have been resolved. The practicality of producing end-user software will then be assessed.

It is inevitable that urban centres - the main setting for non-domestic buildings - will increase in complexity and so provide ever more taxing environments for simulation tools. The techniques described here are designed to meet these challenges.

## Summary

Each new technique represents a significant advance in modelling over traditional prediction methods. Furthermore, they were each designed to be highly scalable. That is, there are very few hard-wired limitations for any of the simulation or the building-model parameters. The daylight prediction technique, for example, can model internal illuminances for a full year using arbitrarily short time-steps. A five or even one minute time-step is feasible with minimal computational overhead because it is simply a matter of re-using daylight coefficients in a fast matrix calculation. A short time-step may be needed to accurately model the performance of daylight responsive lighting controls.

All three techniques were tested early in the development phase using a range of building models, from simple sketchbook designs to highly complex CAD models. The (UNIX) *Radiance* lighting simulation system is used as the rendering engine in each case. *Radiance* can model a wide range of material types e.g., specular and semi-specular reflectors, re-directing prisms, bi-directional reflection-transmission distribution functions, etc., all of which can be based on realistic physical models. There are of course a range of simpler modelling approaches available. These invariably contain fundamental restrictions e.g., small number of polygons for the building model, diffuse-only reflecting surfaces, uniform or overcast-only sky models without sun, etc. For demanding situations, simple tools may offer only partial solutions of questionable accuracy, or may not even work at all.



## Related publications

- Mardaljevic, J. *The BRE-IDMP dataset: A new benchmark for the validation of illuminance prediction techniques* Lighting Res. Technol. 33(2) (2001) (In press)
- Mardaljevic, J. *The Simulation of Annual Daylighting Profiles for Internal Illuminance* Lighting Res. Technol. 32(3) (2000) (In press)
- Mardaljevic, J. and Rylatt, M. *An Image-based Analysis of Solar Radiation for Urban Settings* PLEA 2000 Camb, UK (2000)
- Ward Larson, G. and Shakespeare, R. *Rendering with Radiance: The Art and Science of Lighting Visualization* San Francisco: Morgan Kaufmann. (1998)

For further information and a complete list of related publications, see the author's webpages:

<http://www.iesd.dmu.ac.uk/~jm>

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