Simulating the Thermal Effects of Daylight-controlled Lighting

J A Clarke, M Janak
Energy Systems Research Unit, University of Strathclyde, Glasgow G1 1XJ
email: esru@strath.ac.uk
http://www.strath.ac.uk/Departments/ESRU

Abstract

This paper describes a simulation based method for the integrated performance appraisal of buildings incorporating daylight utilisation technologies. The method utilises the ESP-r [1] and RADIANCE [2] systems, running synchronously, to construct a multi-variate performance picture for a range of models representing alternative design intents.

1. Introduction

The modelling of daylight-responsive buildings requires an accurate prediction of the time varying internal illuminance distribution against temporal events such as blind movement and sky luminance changes.

The *CIE* overcast and clear sky daylight factor method is predominant in contemporary modelling approaches, with many different methods applied to calculate the daylight factors. These methods range from analytical approaches [1, 3], which are appropriate to specific problem types (e.g. rectilinear geometry), to fully generalised lighting simulation programs [2] which can handle problems of arbitrary complexity.

However, the daylight factor concept has an important limitation: daylight factors are subject to considerable variation even under overcast sky conditions. Indeed, variations of the order of 1:5 have been reported [5]. One experiment [6] compared predicted and measured internal illuminance, and the corresponding values for annual lighting energy consumption, for a variety of daylight factor based methods. The results demonstrated that the methods were unable to adequately represent the illuminance resulting from variations in sky conditions. Clearly, the daylight factor method is inadequate for the modelling of problems which combine real sky types with complex building interactions.

Another area of concern relates to luminaire control. The hourly weather data normally employed is incompatible, in its frequency, with the requirements of realistic control algorithms. Some programs, e.g. SUPERLINK [4], offer statistical models to account for the sky luminance variation within the hour interval. However, because the results are provided as hourly integrations, it is not possible to use them to model specific control characteristics (such as photocell position, field of view, time constant, switch-off delay, etc.). The consequences of such omissions have been reported elsewhere [7]. *T*he use of hourly average data will significantly misrepresent the system response.

A more robust method is required to support high frequency internal daylight distribution estimation under realistic assumptions relating to sky conditions, building use and luminaire control. Such a method is reported in the next section.

2. The ESP-r Method

The requirements as laid down for the integrated performance appraisal method were as follows.

- An ability to handle a high frequency variation of the sky luminance distribution.
- Fully 3D, variable building geometry to accommodate movable and light redirecting systems.
- Comprehensive treatment of light transfer by multiple reflections and transmissions.
- Accurate representation of artificial lighting control.
- Full integration of the approach within the overall building/ HVAC energy simulation.

Two modelling approaches have been developed. The first is based on the direct conflation of the ESP-r and RADIANCE systems, within a *UNIXä* platform, and with the former system providing the overall supervisory control at simulation time as shown in Figure 1.

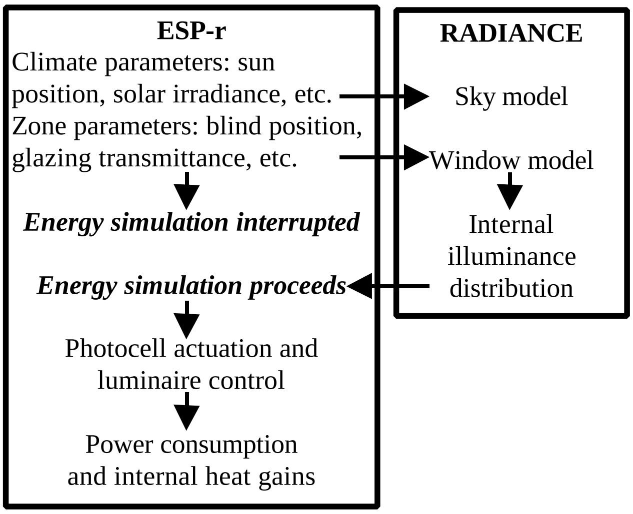

Figure 1: ESP-r/ RADIANCE interactions at the time-step level.

At each simulation time-step, ESP-r's luminaire control algorithm initiates the daylight simulation. RADIANCE is then driven by ESP-r to carry out several tasks as follows: (1) transfer of data defining current climate and zone state; (2) generation of sky model; (3) calculation of internal illuminance for defined sensor locations; (4) transfer back of illuminance data to luminaire controller. The returned data are then used to determine, as a function of the active control algorithm, the luminaire status and hence the casual gain associated with lights at the current time-step. While this approach supports problems of arbitrary complexity, it is computationally demanding and therefore inappropriate for routine design application where problems may be characterised in terms of a finite number of discrete states (e.g. blind open, partially closed and closed).

For such problems, a second approach was developed in which the internal illuminance calculation is based on a daylight coefficient method [8]. This method subdivides the sky vault into 145 elements (see Figure 2) and then calculates a coefficient for each element with an arbitrary luminance imposed. This is repeated for each problem case. The daylight coefficients are determined from:

$$DC_i = \frac{E_i}{L_i . w_i} \tag{1}$$

with the total photocell illuminance signal given by:

$$E_{tot}^{t} = E_{sky}^{t} + E_{sun}^{t} \tag{2}$$

$$E_{sky}^{t} = \sum_{1}^{145} DC_i . L_{i,sky}^{t} . w_i \tag{3}$$

$$E_{sun}^{t} = DC_{i(sun)} . E_{d,n,sun}^{t} \tag{4}$$

where DC_i is the daylight coefficient of the *i*th sky element (-), E_i is the sensed illuminance relating to sky element *i* (lux) , L_i is the luminance of sky element *i* (cd/m^2), w_i is the solid angle of sky element *i* (str), E_{tot}^{t} is the (time dependent) total photocell illuminance signal (lux), E_{sky}^{t} is the (time dependent) sky diffuse photocell illuminance (lux), E_{sun}^{t} is the (time dependent) direct sun photocell illuminance (lux), $L_{i,sky}^{t}$ is the (time dependent) luminance of sky element *i* (cd/m^2), $DC_{i(sun)}$ is the daylight coefficient corresponding to the actual sun position (-) and $E_{d,n,sun}^{t}$ is the direct normal sun illuminance (lux).

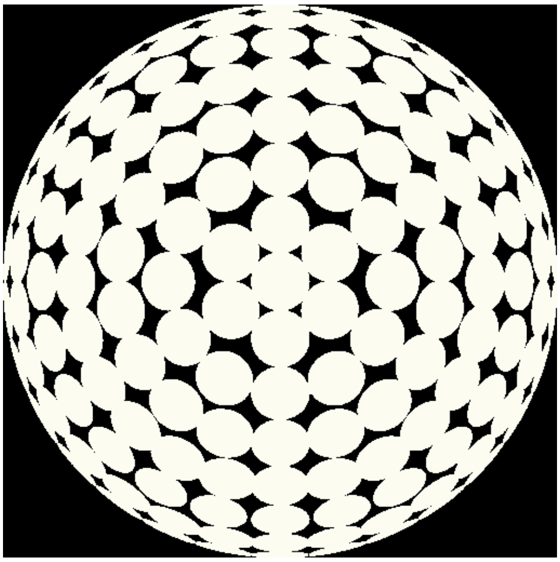

Figure 2: Sky vault subdivision for daylight coefficient calculation.

The daylight coefficients for each sensor point and problem case are calculated prior to the energy simulation using RADIANCE. Then, at simulation time, the complex internal illuminance distribution can be determined by simple multiplications and additions.

The Perez sky luminance distribution model [9] is used in conjunction with direct normal and diffuse horizontal solar irradiance data. Several weather collections/ algorithms exist by which these data may be obtained at higher than normal frequency: e.g. the 5 minute average data from the *International Daylight Measurement Program* [10] stations, or the use of a probability density algorithm [11] to generate high frequency irradiance data from hourly values.

In essence, ESP-r supports luminaire and shading device control on the basis of the value of any model parameter (although some combinations are not supported because they are unrealistic). For example, window blind control may be achieved on the basis of the internal zone air temperature or illuminance, or on the basis of the ambient air temperature or facade irradiance. Luminaire control may be based on the illuminance at a given point or averaged across several points representing some zone of interest. Likewise, control parameters may be imposed in terms of aspects such as photocell position, vision angle, controller set-point, switch-off lux level, switch-off delay time and minimum stop. For example, two explicit dimming control algorithms have been implemented within ESP-r.

An *integral reset* controller which adjusts the dimming level so that the measured photocell signal is kept at a constant reference value. This reference level is set during night-time photocell calibration and represents the measured signal from the artificial lighting. The dimming level in the controller dynamic range is determined as:

$$f_{\dim}^{t} = 1 - \frac{E_{d,s}^{t}}{E_{e,s}} \quad . \tag{5}$$

A *closed loop proportional* controller which adjusts the dimming level so that it is a linear function of the difference between the photocell signal and the night-time reference level. With this controller, a day-time calibration must be performed to determine the linear control function slope for use in the following expression.

$$f_{\dim}^{t} = \frac{1 + m_{slope}.\left(E_{d,s}^{t} - E_{e,s}\right)}{1 - m_{slope}.E_{e,s}} \tag{6}$$

where $f_{\dim}^{t}$ is the time varying dimming level (-), m_{slope} is the slope of the controller's linear function determined by day-time calibration, $E_{d,s}^{t}$ is the time varying daylight photocell signal (lux), and $E_{e,s}$ is the artificial lighting photocell signal during night-time calibration (lux).

3. A Case Study

To demonstrate the application of the above method, consider the problem shown in Figure 3: an office with dimension 4.5m x 4.5m x 3.2m with a combination window comprising an upper portion with integral/ external light shelf and a lower portion with a movable blind. The office is to be lit by wall mounted, asymmetric luminaries designed to provide an average workplace illuminance of *320 lux*. The lamp luminous output can be regulated between 10% and 100% of the full light output. Daylight responsive control is implemented via a ceiling mounted photocell located at *2/3* of the room depth.

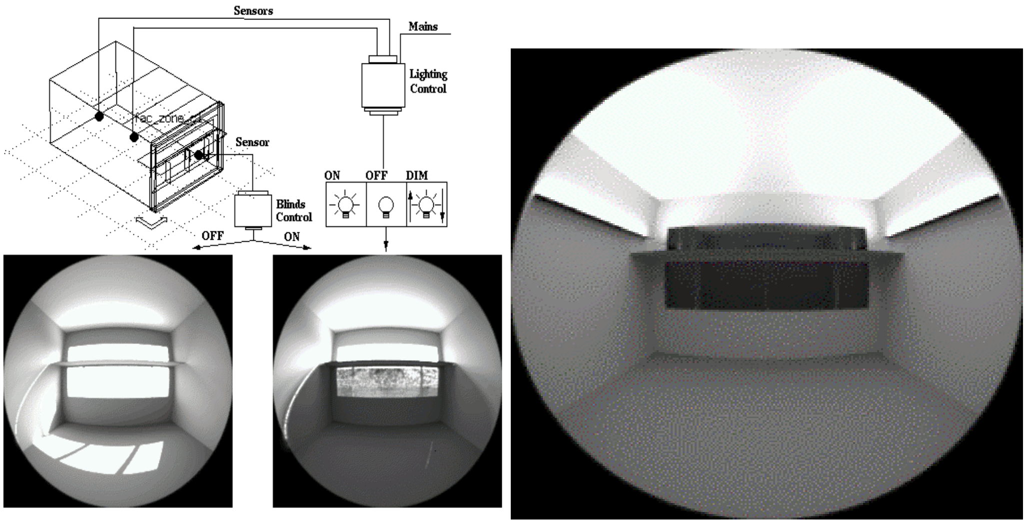

Figure 3: Thermal/ lighting model configuration (right); office with wall mounted, asymmetric luminaires during night-time calibration (left).

Within the study, the following control parameters were applied:

- daylight sensor set-point - 320 lux;
- switch-off light reference level - 150% of set-point;
- minimum light dimming - 10% of full light output;
- minimum power dimming - 10% of full circuit power;
- switch-off delay time - zero for 60 minutes time-step simulations; 15 minutes for 5 minute time-step simulations;
- blind control sensor location - vision window plane measuring vertical global irradiance;
- set-point for blind rotation to the shading position (45^o) - 300 W/m^2

Figure 4 shows a comparison between two photocell geometries: a partially shaded case ($E_{e,s}$ = *44.5 lux*) and a fully shaded case ($E_{e,s}$ = *14.1 lux*). For the closed loop, proportional control action considered here, the linear control slope, m_{slope} , was set at -0.023 for the partially shaded case and -0.056 for the fully shaded case.

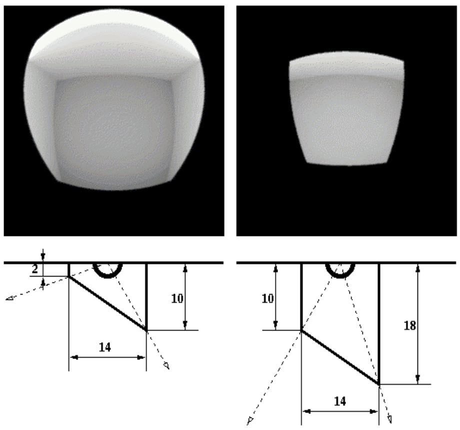

Figure 4: Partially and fully shading photocell geometry
(top figure shows sensor’s view from ceiling towards floor and walls.

Table 1 shows the predicted power consumption for the different controller, photocell and simulation approaches studied, while Figure 5 shows the predicted illuminance variation at selected locations.

Table 1: Comparison of predicted lighting power consumption for studied cases.

Case	Time-step (minutes)	Lighting power consumption (Wh/day)	Relative difference (%)
Integral reset partially shaded sensor	5	1168.2	-32.5
Integral reset fully shaded sensor	5	997.0	-42.4
Closed loop proportional partially shaded sensor	5	1670.4	-3.4
Closed loop proportional fully shaded sensor	5	1636.0	-5.4
Closed loop proportional partially shaded sensor	60	1792.2	+3.6
Ideal control	60	1730.0	0.0

These results give rise to some interesting observations. It is clear that to achieve realistic lighting control behaviour, short-term daylight availability should be considered. It is also clear that the different controllers result in large differences in estimated power consumption (c.f. integral reset vs. closed loop action). On the other hand, a properly calibrated closed loop proportional controller will give rise to the same power consumption as a more traditional simulation approach (i.e. ideal control with 60 minutes time step). With an integral reset controller application, the ideal control approach will fail to reproduce the dynamic behaviour and predict the correct power consumption. It is clear therefore that the developed methods allow explicit modelling of the many important interactions that occur between the thermal and visual domains.

4. Conclusion

A method has been developed which allows an integrated simulation of the thermal and lighting behaviour of buildings with realistic operational aspects imposed. The method is based on a conflation of the ESP-r and RADIANCE systems, with the former system controlling the interaction. Two modes of operation have been implemented corresponding to interaction at the time-stepping level and the pre-simulation construction of daylight coefficients for discrete problem cases.

The outputs that result - defining internal illuminance, visual comfort and luminaire power saving - are then treated as one part of ESP-r's multi-variate perfoemance appraisal as represented by the Integrated Performance View (IPV) shown in Figure 6. ESP-r's IPV approach is described elsewhere [12].

5. Further Reading

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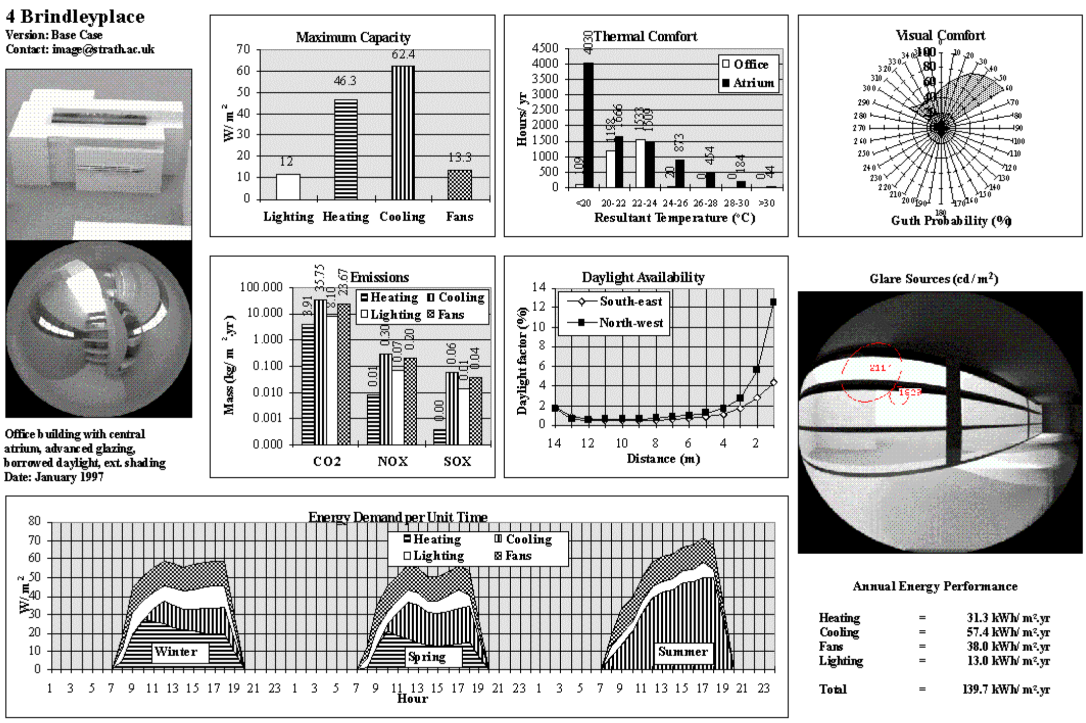

Figure 6: An example of an ESP-r generated IPV.

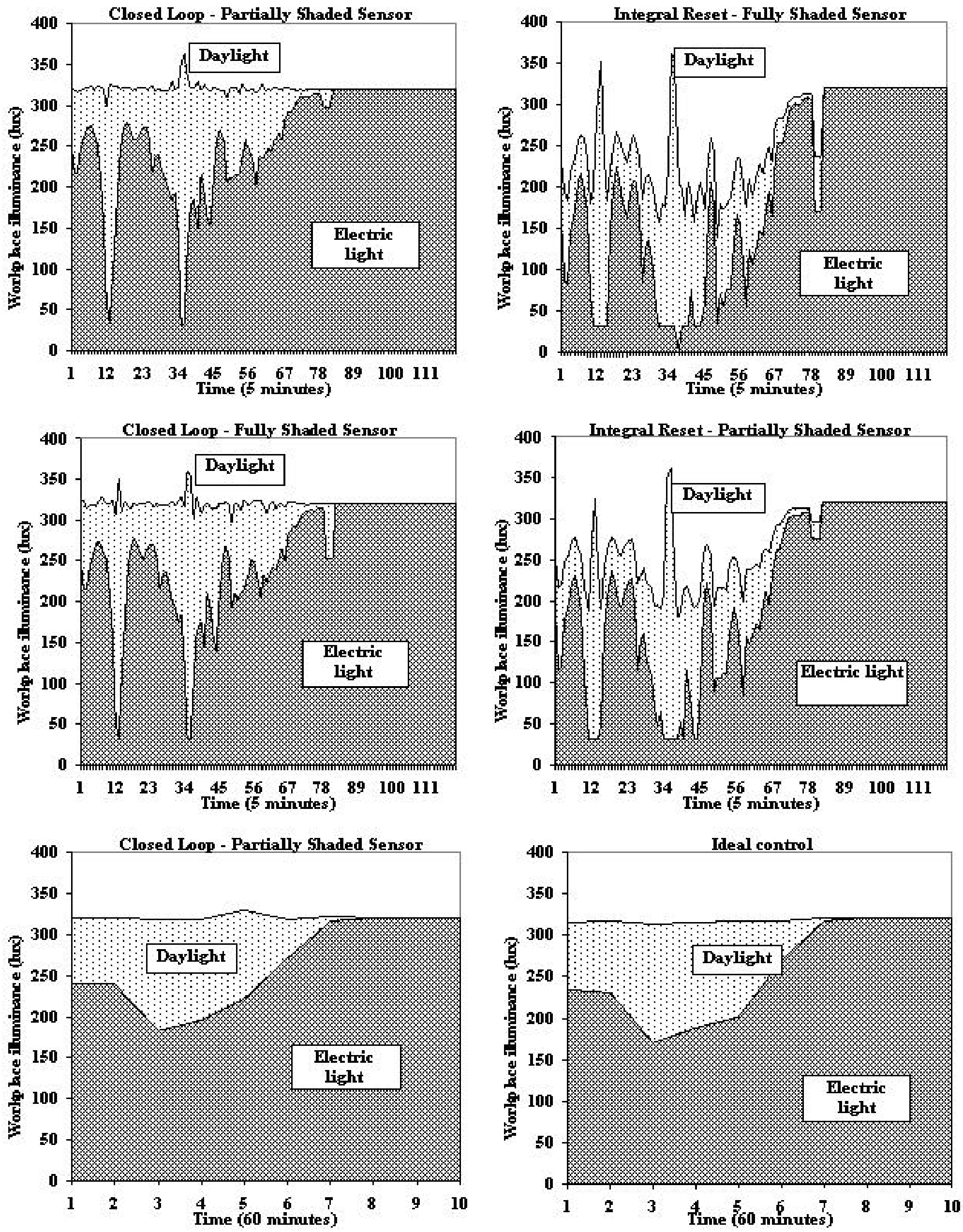

Figure 5: Average predicted light level at selected locations.