CURRENT STATE-OF-THE-ART OF INTEGRATED THERMAL AND LIGHTING SIMULATION AND FUTURE ISSUES

Milan Janak[*/**] and Iain Macdonald[**]
[*]Slovak Technical University,
Radlinského 11, 813 68 Bratislava, Slovakia.
[**]Energy Systems Research Unit,
University of Strathclyde, Glasgow G1 1XJ, Scotland.

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 or in pre-simulation mode, to construct a multi-variate performance picture for a range of models representing alternative design intents.

INTRODUCTION

The recent rapid technological advancement in transparent building envelope systems such as advanced solar control glazing with managed blind systems, electrochromic, thermochromic and photochromic glazing, redirecting systems, TIMs and photo-electrically controlled artificial lighting have brought the real challenge of an integrated building design into practice.

Given the rapid rate of introduction of these new technologies into the construction market place, there is at present very little or almost no practical experience with the integration of these systems into buildings. In the light of these developments, integrated building thermal and lighting simulation can play a significant role in assisting the design and research community to grasp a more complete understanding of the underlying integration issues.

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.

Work in this area has been ongoing for many decades. A number of different approaches have been suggested and implemented up till now. These range from simple analytical approaches e.g. [1, 3] to more complex models [4], usually using standard (overcast, clear) sky luminous distribution patterns to translate into other possible insolation conditions. These approaches have an important limitation: external to internal daylight ratios 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 that combine real/modelled sky types with complex building interactions.

Recent advances in the development and validation of sky luminous distribution models e.g. [7] and powerful local and global illumination simulation [2] have brought new more advanced approaches. Two trends can be found. Direct use of powerful ray tracers [2] in their native mode together with reduction/ compression of insolation/ sun position conditions [8] in order to save simulation time by avoid simulating the same/ similar cases.

Another strong trend is directed toward sky vault discretisation, calculating *daylight coefficients* [9, 10]. Powerful ray tracers [2] are employed prior to the thermal simulation to calculate the set of daylight factors. The complex illumination equation is then reduced to simple/ fast multiplication and addition operations at simulation time.

According to the author’s current knowledge none of these methods has been fully integrated with any of the existing thermal simulation programs. Typically these methods have been programmed into standalone programs with no or pseudo integration with a thermal domain (i.e. feedback between domains and control interactions at a time step level are not possible).

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 integrals, it is not possible to use them to model dynamic response of the control. The consequences of such omissions have been reported elsewhere [11]. The 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.

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 approach is based on the direct conflation of the ESP-r and RADIANCE systems, within a *UNIX* platform, and with the former system providing the overall supervisory control at simulation time as shown in Figure 1.

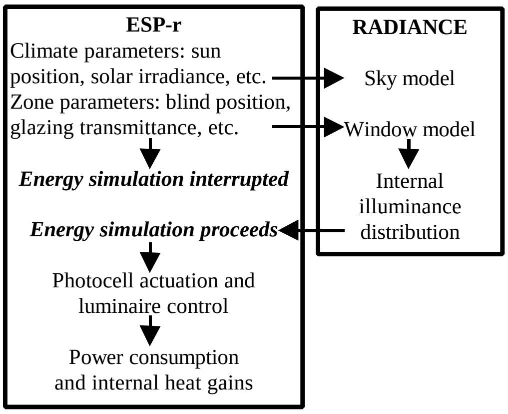

Figure 1. ESP-r/ RADIANCE interactions at the time-step level.

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. Detailed explanation of this approach has been already extensively published e.g. [12].

To reduce the computationally demanding nature of the direct coupling method the reuse of already calculated data was proposed. The essence of this method is that if certain characteristics of the calculation are similar to those of a previous calculation then the sensor value will be similar.

The main difficulty in defining such a scheme is that the variation of the sensed value is a complex function of many parameters. In Figure 2 the sensed illuminance (for partially shaded ceiling mounted photocell see Figure 5) has been plotted as a function of external direct and diffuse illuminance for a three day period of similar insolation conditions.

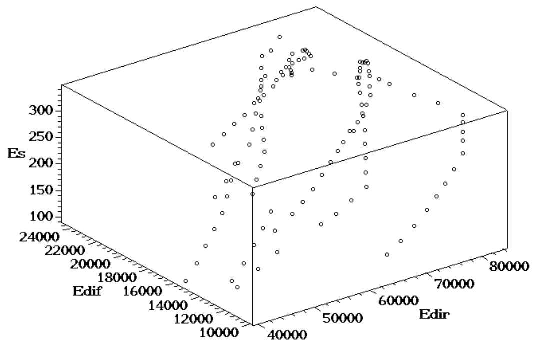

Figure 2. Example of the complex relationship between sensed illuminance (E_s), diffuse horizontal (E_{dif}) and direct normal (E_{dir}) illuminance.

However only five parameters vary between the calls to RADIANCE:

- Sun position (azimuth and elevation)
- Sky illuminance (direct and diffuse)
- Blind state

The model presented in Figure 9 was subjected to a sensitivity analysis. This confirmed the complex nature of the problem and that the various parameters interact in a synergistic manner.

However the complexity of the problem can be reduced by initially selecting a subset of database entries which correspond to a similar geometry of two or more models already analysed. The parameters identified for this reduction phase are the sun position (azimuth and elevation) and blind state, see Figure 3 (for partially shaded ceiling mounted photocell). It has been discovered that if the sun position is within 5 degrees of a previously calculated sun position then the two geometries are effectively the same. This angle is defined as the angle between the two direction vectors of the sun positions, hence taking into account changes in azimuth and elevation. The linear nature of lighting systems can now be exploited and a simple interpolation between previously calculated points can be used to estimate the sensed illuminance.

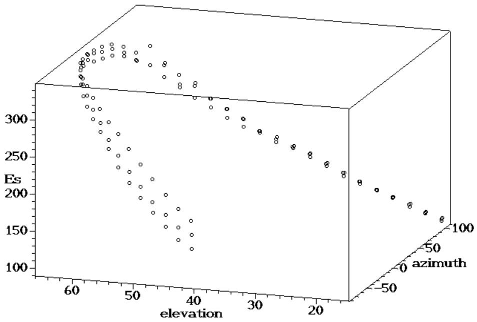

Figure 3. Example of the relationship between sensed illuminance (E_s) and sun position.

It has been estimated that this procedure can reduce the simulation time by between 33-50%, although there will always be conditions where greater or lesser reductions will exist. Further refinements of the process will involve identifying cut off points in relation to the current control scheme whereby the resulting sensed value will be either very high or very low and thus the state of the system can be deduced without the need of a RADIANCE simulation.

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 [13]. This method subdivides the sky vault into 145 elements (see Figure 4) 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:

$$DC_i = \frac{E_i}{L_i . w_i} \quad (1)$$

with the total photocell illuminance signal given by:

$$E_{tot}^t = E_{sky}^t + E_{sun}^t \quad (2)$$

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

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

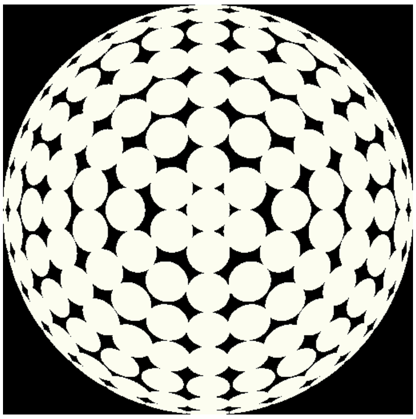

Figure 4. Sky vault subdivision for daylight coefficient calculation.

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 [7] 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* [14] stations, or the use of a probability density algorithm [15] 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 [10] that 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:

$$f_{\dim}^{t} = 1 - \frac{E_{d,s}^{t}}{E_{e,s}} \qquad (5)$$

A closed loop proportional controller [10] 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.

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

In the case of these control algorithms more realistic photocell geometry can be simulated as well (see Figure 5).

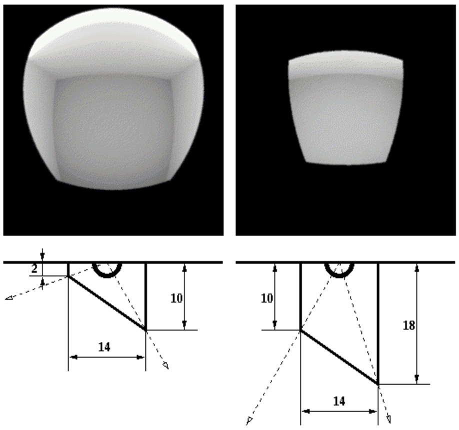

Figure 5. Partially and fully shading photocell geometry (top figure shows sensor's view from ceiling towards floor and walls).

Figure 6 to Figure 8 demonstrate the important differences in predicting dynamic lighting control response for a particular control algorithm. 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 (e.g. integral reset vs. closed loop action results in 30% to 40% different power consumption prediction). 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.

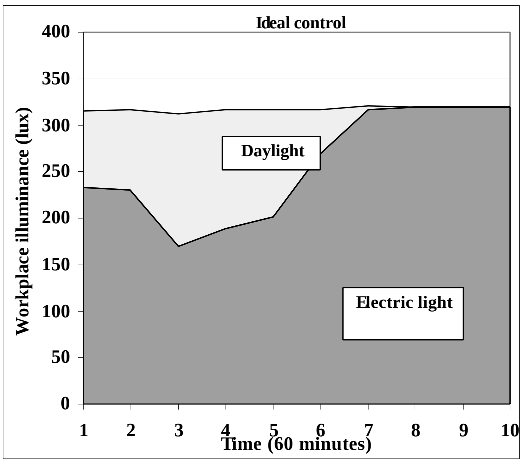

Figure 6. Predicted resulting illuminance levels for the case of ideal dimming control with typical hourly climate data resolution.

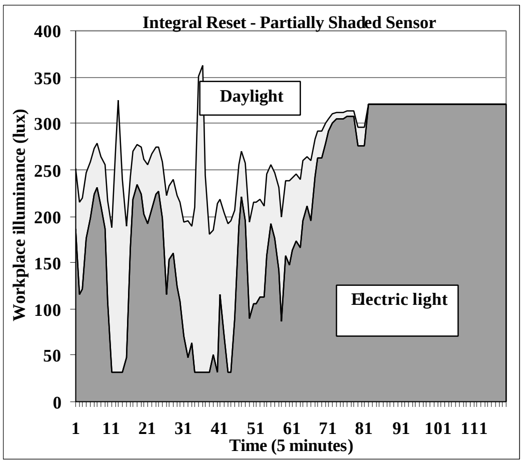

Figure 7. Predicted resulting illuminance levels for the case of integral reset dimming control with 5 minute climate data resolution.

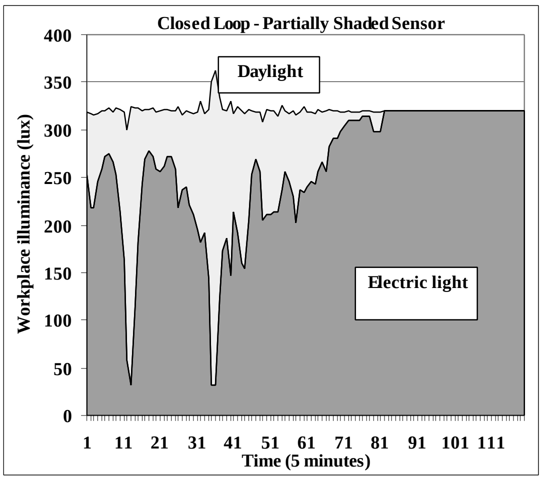

Figure 8. Predicted resulting illuminance levels for the case of closed loop proportional dimming control with 5 minute climate data resolution.

METHOD VALIDATION

In our work we have considered RADIANCE native calculation as a valid reference. RADIANCE in its native calculation mode has been already extensively validated by many researches e.g. [16] and its practical accuracy has been confirmed.

Our goal was to validate daylight coefficient method against RADIANCE. The validation has been carried out for two types of the photocell sensors. The partially shaded ceiling mounted sensor (see Figure 5) and the second hemispherical work plane mounted sensor, both placed in a cellular office with a light shelf (see Figure 9).

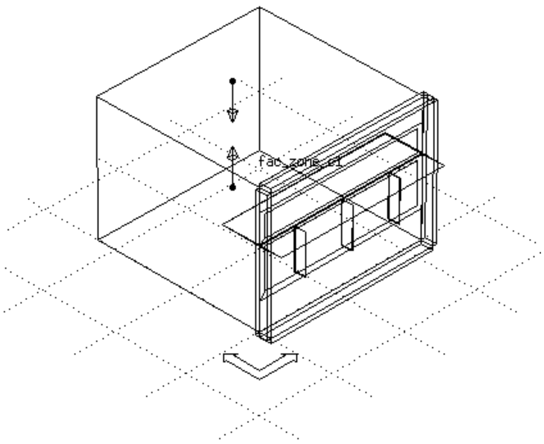

Figure 9. Model of the cellular office with the light shelf used in the validation study with indication of the photocell locations.

The photocell's illuminances have been calculated with both methods over the month of April of the test reference year for Bratislava, Slovakia which has a fair distribution of different insolation conditions. Figure 10 and Figure 11 show the comparison of calculated illuminances between RADIANCE and daylight coefficient method together with an error analysis for the both sensor types.

These results give rise to some interesting observations. It is obvious that implemented daylight coefficient method has much better performance for shaded ceiling mounted photocell (see Figure 10). Considering the practical dynamic range of illuminances for a ceiling mounted photocell (e.g. 0 – 350 lux) we can see from Figure 10 that accuracy of the daylight coefficient method is more then safisfactory for this case.

However, looking at the results for the hemispherical work plane sensor (see Figure 11) it is obvious that for this case the implemented daylight coefficient method has some room for an improvement.

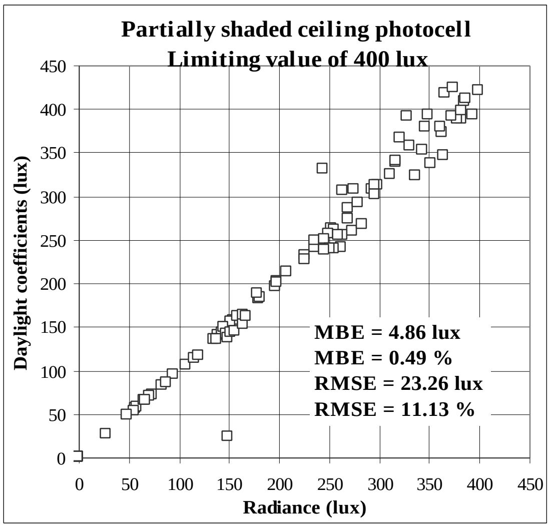

Figure 10. Validation results for daylight coefficient method for the case of a partially shaded ceiling mounted photocell.

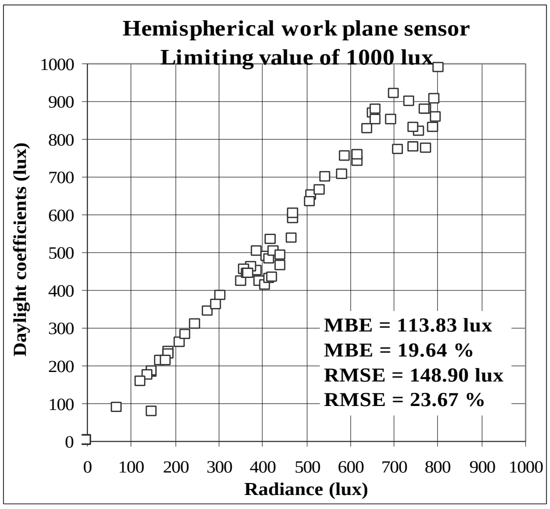

Figure 11. Validation results for daylight coefficient method for the case of a hemispherical work place mounted photocell.

Further analysis has shown that it is the direct sun/ sky illuminance contribution with brings the largest error into the daylight coefficient calculation, as also reported by [9]. This is caused by insufficient sky vault discretisation resolution (i.e. only 145 patches) use to calculate direct sun/ sky contributions.

Further development of the implemented daylight coefficient method is directed towards the implementation of a variable sky vault discretisation scheme and into the separation of direct and indirect calculations.

The implemented method gives satisfactory results for most commonly used photocell mounting and geometry. However, the method as currently implemented is not generally robust and care must be taken with its application to the different configurations.

A CASE STUDY

To demonstrate the application of the above methods, the design study from EU IMAGE (IMplementation of Advanced Glazing in Europe) [17] is presented. The aim of the simulation in the project was to assess integrated performance of the advanced glazing by constructing multi-variate building performance picture IPV (Integrated Performance View).

Figure 12 shows IPV for the case with electrochromic double glazing unit and Figure 13 for the case with spectrally selective solar control double glazing unit when applied to the office building of Britannia House located in the City of London. Table 1 shows some component based performance parameters for the studied glazing systems.

Table. 1. Component based performance parameters for studied double glazing units.

Performance Parameter	Electrochromic glazing	Solar control glazing
T_v (-)	0.50 (0.10)	0.65
T_s (-)	0.26 (0.03)	0.33
$T_{s, tot}$ (-)	0.40 (0.10)	0.42
U ($W.m^{-2}.K^{-1}$)	1.40	1.30

Daylight responsive control of artificial lighting and electrochromic glazing is implemented via a ceiling mounted photocell located at *2/3* of the room depth. Within the study, the following control parameters were applied:

- Closed loop proportional (dimming) lighting control;
- Fully shaded ceiling photocell with set point of 14.1 lux coresponding to 320 lux at working plane;
- Workplane to sensor ratio of 22.7 determined by night time calibration;
- Linear control slope m_{slope} of -0.056;
- Switch-off set-point at 150% of the set-point, i.e. 480 lux;
- Luminous dimming range of 100% - 10%;
- Electric dimming range 100% - 30%;
- Integral reset - constant "lux" maintenance control for electrochromic glazing dimming;
- Electrochromic control with ceiling photocell set point of 35.5 lux coresponding to 500 lux at work plane;
- Workplane to sensor ratio of 14.1 determined by daytime calibration.

By comparison of multivariate performance criteria between IPV for electrochromic glazing (see Figure 12) and IPV for advanced solar control glazing (see Figure 13) for the Britannia House design study, the following conclusions can be drawn:

- Electrochromic glazing has marginal influence on maximum heating capacity and offers a 33% reduction in maximum cooling capacity.
- Electrochromic glazing offers a 31% reduction in cooling energy consumption and an increase in heating (2.5%) and lighting (13.5%) energy consumption. Resulting reduction in total energy consumption is 10%.
- The application of electrochromic glazing to the office facades offers a significant improvement in summer thermal comfort. Number of working hours with dry resultant temperatures in the range from 24^{o}C to 26^{o}C has been reduced by 300 hours.
- Electrochromic glazing will insignificantly decrease the daylight availability but will not change its characteristic distribution. This is reflected by insignificant increase in the artificial lighting energy consumption.
- Electrochromic glazing system examined will significantly improve visual comfort for VDU working environment for most of the time. However, for the case of a direct sun light penetration into the office the visual field luminances will exceed recommended level.
- Electrochromic glazing system will significantly improve demand side management potential by reducing demand peaks particularly for cooling.

CONCLUSIONS

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 following areas have been identified for further research and development:

- Implementation of a variable sky vault discretisation scheme and separation of direct and indirect calculations in the case of implemented daylight coefficient method with aim to arrive at robust method for any type of photocell geometry and location;
- Implementing luminary coefficients for an explicit artificial lighting simulation;
- Development of simulation for complex window control systems based on the occupants or

system responses (supervisory controls, visual, thermal comfort controls etc.);

- Implementing a structure for handling complex bi-directional reflectance transmittance distribution functions (BRTDFs) [18] as a means to enable simulation of the complex fenestration systems.

REFERENCES

1. Clarke, J. A., Energy Simulation in Building Design. Adam Hilger Ltd., Bristol 1985.
2. Ward, G. J., The Radiance Lighting Simulation System, Global Illumination, Siggraph '92 Course Notes, July 1992.
3. Winkelmann, F. C., Selkowitz, S., Daylighting Simulation in the DOE-2 Building Energy Analysis Program. Energy and Buildings, 8 ,pp. 271 - 286, 1985.
4. Szerman, M., Auswirkung der Tageslichtnutzung auf das energetische Verhalten von Burogebauden. Doctoral thesis, Stuttgart, 1994.
5. Teregenza, P. R., The daylight factors and actual illuminance ratios. Lighting Research and Technology. Vol. 12, No. 2, pp 64 - 68, 1980.
6. Littlefair, P. J., Modelling Daylight Illuminance in Building Environmental Performance Analysis. Journal of the Illuminating Engineering Society, pp 25 - 34, Summer 1992.
7. Perez, R., Seals, R., Michalsky, J., All-Weather Model for Sky Luminance Distribution-Preliminary Configuration and Validation. Solar Energy Vol. 50. No 3. pp. 235 - 243, 1993.
8. Herkel, S., "Dynamic link of light – and thermal simulation: on the way to integrated planning tools", Fifth International IBPSA Conference, September 8 – 10, 1997, Prague, pp. 307 – 312.
9. Cropper, P., Mardaljevic, J., Lomas, K. J., Lyons, A. R., "Predicting time-varying illuminances in complex spaces with inovative glazing and lighting systems", Final report on EPSRC grant GR/J88753, IESD De Montfort University, 1997.
10. Tsangrassoulis, A., Santamouris, M., "Daylight modelling with Passport-Light", Fifth International IBPSA Conference, September 8 – 10, 1997, Prague, pp. 73 – 78.
11. Rubinstein, F., Ward, G., Verderber, R., Improving the Performance of Photo-Electrically Controlled Lighting Systems. Journal of the Illuminating Engineering Society, pp 70 - 94, Winter 1989.
12. Janak, M., "Coupling building energy and lighting simulation", Fifth International IBPSA Conference, September 8 – 10, 1997, Prague, pp. 313 – 319.
13. Littlefair, P. J., Daylight Coefficients for Practical Computation of Internal Illuminance. Lighting Research and Technology. 24 (3) pp. 127 - 135, 1992.
14. JOU2-CT 920144 CIPD-CT 925033 Availability of Daylighting – Design of a European Daylighting Atlas. Luminous Climate in Central Europe. Final report, ICA SAS Bratislava, December 1995.
15. Skartveit, A., Olseth, J. A., The Probability Density and Autocorrelation of Short-Term Global and Beam Irradiance. Solar Energy Vol. 49. No. 6. pp. 477 - 487, 1992.
16. Mardaljevic, J. "Validation of a lighting simulation program under real sky conditions", Lighting Reseach and. Technology 27(4), 1995 pp. 181 – 188.
17. IMAGE (1997) IMAGE Newsletter, available from HGa Ltd, Burderop Park, Swindon. Wiltshire SN4 0QD.
18. Aydinli, S., at el., "Measurement of photometric characteristics of daylighting systems", Conference proceedings Daylighting'98, May 11 – 13 1998, Ottawa, pp. 247 – 254.

NOMENCLATURE

DC_i - daylight coefficient of the *i*th sky element (-),
E_i - sensed illuminance relating to sky element *i* (lux) ,
L_i - luminance of sky element *i* (cd/m^2),
w_i - solid angle of sky element *i* (str),
E^t_{tot} - time dependent total photocell illuminance signal (lux),
E^t_{sky} - time dependent sky diffuse photocell illuminance (lux),
E^t_{sun} - time dependent direct sun photocell illuminance (lux),
$L^t_{i,sky}$ - time dependent luminance of sky element *i* (cd/m^2),
$DC^t_{i(sun)}$ - daylight coefficient corresponding to the actual sun position (-),
$E^t_{d,n,sun}$ - direct normal sun illuminance (lux),
$f^t_{\dim}$ - time varying dimming level (-),
m_{slope} - slope of the controller's linear function determined by day-time calibration,
$E^t_{d,s}$ - time varying daylight photocell signal (lux),
$E_{e,s}$ - artificial lighting photocell signal during night-time calibration (lux),
T_v - normal visible transmittance (-),
T_s - normal solar transmittance (-),
$T_{s,tot}$ - normal total solar energy transmittance (-),
U - thermal transmittance value (W.m^{-2}.K^{-1}).

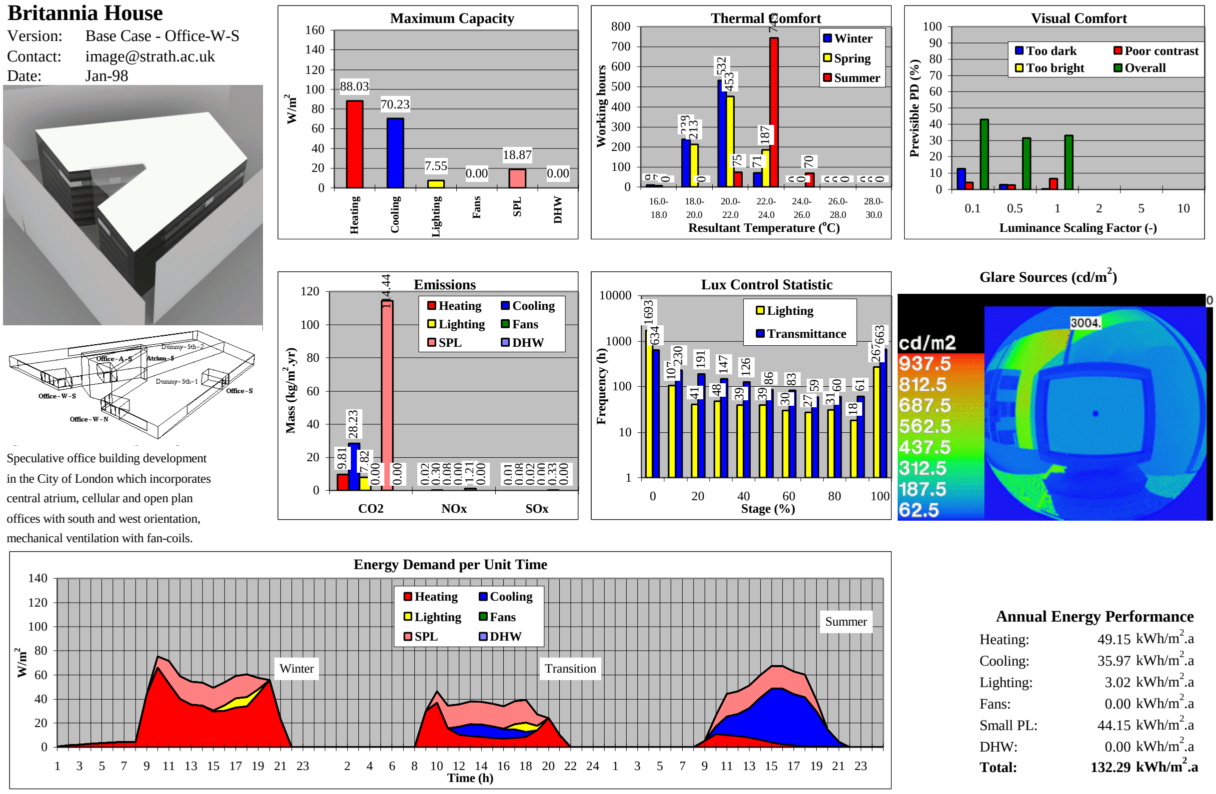

Figure 12. The integrated performance view for the case with electrochromic double glazing unit for Britannia House design study.

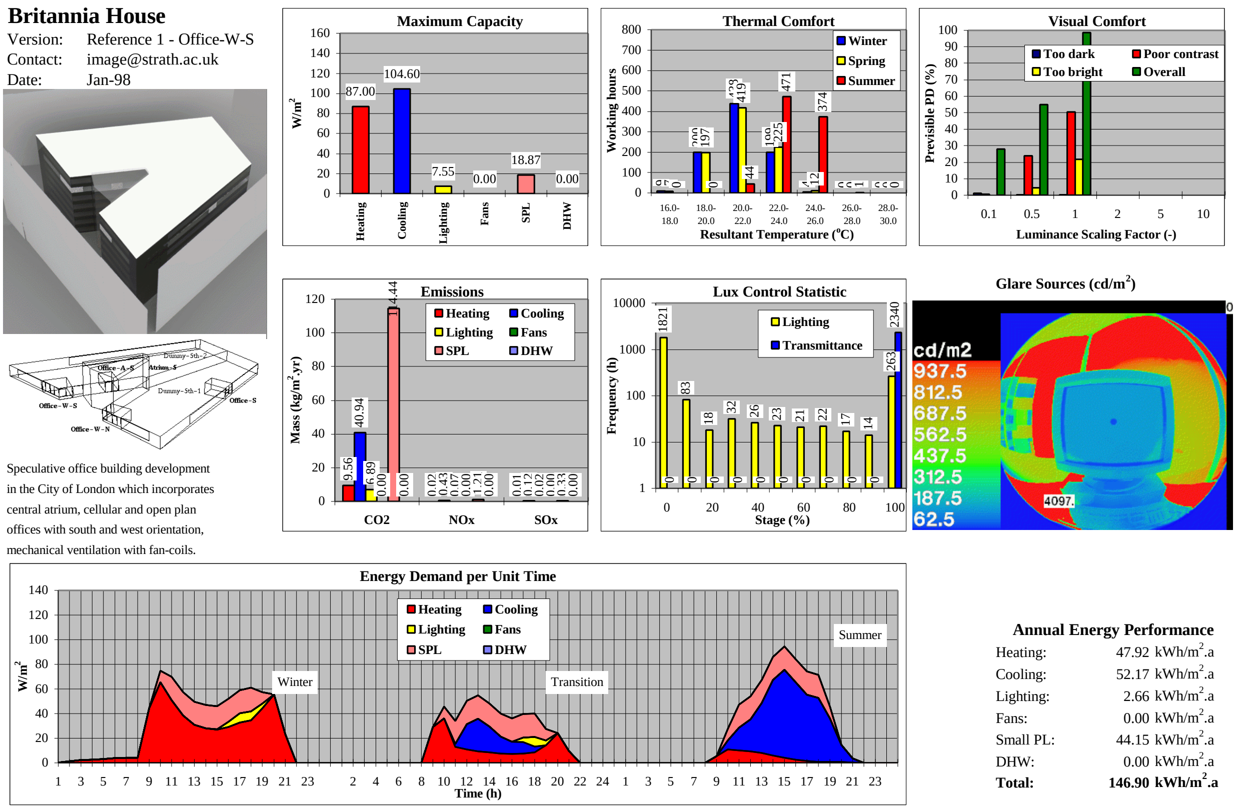

Figure 13. The integrated performance view for the case with spectrally selective solar control double glazing unit for Britannia House design study.