

## EVALUATION OF SHADING DEVICES USING A HYBRID DYNAMIC LIGHTING THERMAL MODEL

R. Ajmat Arch., J. Mardaljevic Bsc MPhil PhD and V.I. Hanby Bsc PhD  
Institute of Energy and Sustainable Development (I.E.S.D.)  
De Montfort University, Queens Building  
The Gateway, Leicester LE1 9BH, UK  
Tel. +44 116 2577966, Fax +44 116 2577981  
Email: rajmat@dmu.ac.uk

### ABSTRACT

The thermal modelling of windows is often carried out at a high level of precision whilst irradiance and daylight quantities are predicted using coarse approximations. This paper describes a new approach to predict the daylighting and thermal performance of buildings with shading devices using a hybrid dynamic lighting-thermal model. Irradiance and daylighting modelling is carried out using the validated *Radiance* lighting simulation program. The irradiance predictions coming from raytracing calculations on virtual photocells provide input to a simplified thermal response model. The new technique is applied to the problem of evaluating shading devices in terms of overall energy and visual comfort performance for multiple climate zones.

### INTRODUCTION

Many parts of the developing world are experiencing rapid growths in urbanisation. This has created a huge expansion in construction activity to produce the needed non-domestic and domestic buildings. This rapid growth, especially in China, has resulted in the widespread abandonment of 'traditional' architectural styles, which were often climatically adapted to their locale, in favour of quick-build, low-tech generic building types.

Although not commonly equipped with air conditioning, it is inevitable that, with increasing prosperity, there will be increasing demand to cool buildings that tend to overheat. The demand is likely to be the greatest for those buildings currently being constructed that pay little heed to the principles of climatic building design, i.e. the generic concrete building that is often prone to high levels of solar gain. External shading devices are one of the few low-tech architectural features that have the potential to ameliorate solar gain and improve the environment of otherwise unremarkable generic buildings. To be effective, shading devices need to be optimised to achieve a balance between the heating, cooling and lighting of a building. In short, the accurate prediction of entrant

irradiation is a pre-requisite to determining this balance. In this paper, we describe the simulation framework and first results of a system tailored to the evaluation of low-tech buildings in the developing world.

The dynamic daylight and irradiance quantities are predicted using the rigorously validated *Radiance* lighting simulation program [Mardaljevic, 2000a]. The dynamic prediction of daylight in response to climate has recently been demonstrated by a number of authors [Mardaljevic, 1998];[Reinhart et al., 2001];[Janak et al., 1999]. However, the daylight factor is still the most widely used daylight evaluation method, and the dynamic prediction of daylight is considered a relatively novel technique. The dynamic thermal response of a single-zone building is predicted using a simplified nodal model. This is an established technique that has proven to be of comparable accuracy to more complex dynamic thermal models for single zone spaces [Crabb et al., 1987].

The rationale for the hybridization is as follows. Dynamic thermal programs such as ESP-r and EnergyPlus can accurately model heat transfer and thermal storage effects for many building scenarios. Where these programs are perhaps weakest is in the prediction of incident solar irradiation on glazing when shading devices are present. The sky diffuse and inter-reflected components cannot, in the main, be accurately modelled using the standard algorithms present in even the most advanced thermal programs, e.g. ESP-r [Clarke, 2001] and EnergyPlus [Winkelmann, 2001]. Solar radiation can be one of the major energy fluxes in building simulation. Furthermore, the potential for daylighting will depend of the magnitude and the distribution of entrant solar radiation. Accordingly, the accurate prediction of solar radiation is needed to predict the energy budget for the space. The *Radiance* lighting simulation program has undergone numerous validation tests and has been proven to be capable of very high accuracy.

Here, we make the case that, when shading devices are present, the accurate computation of incident irradiance on the glazing should be determined using Radiance, whilst the dynamic thermal processes can be adequately accounted for using a simple nodal model. We propose that, with this combination, a *commensurate* level of precision is achieved for each of the modelling processes.

A link between Radiance and a dynamic thermal programme has been demonstrated in previous research by others [Janak, 1997];[Herkel, 1997] and [Janak et al,1999]. Herkel described an approach of binning annual sky conditions for dynamic calculations, Janak used *Radiance* to predict an irradiation time-series for input to ESP-r for a thermal analysis. In contrast to that work, we use an explicit 3D model of the building only for the *Radiance* simulation. Furthermore, we expand on the analysis described by Janak to (i) include a dynamic daylighting simulation, and (ii) employ the newly proposed “useful daylight illuminance” metric to assess the overall daylight provision [Nabil, 2005]. A further novel aspect of the research is that the hybridization was designed for the rapid evaluation of parametric variation in building parameters, including orientation and climate.

## METHODOLOGY

The simulation framework was conceived to allow rapid evaluation of building designs where there are a number of parametric design options. Part of the aim was to maximise the number of building scenarios that could be evaluated by exploiting efficiency features of the prediction techniques. Key amongst those are (i) the daylight coefficient approach (used to predict time varying irradiance and illuminance), and (ii) the nodal dynamic thermal model (used to predict the heating and cooling load of the building).

In the daylight coefficient approach, the time-varying irradiance and illuminance quantities are derived from pre-computed daylight coefficient matrices (DCMs). It is these DCMs that are computationally the most expensive to compute. The time-varying irradiance and illuminance quantities provide input to the dynamic thermal model. The entrant solar irradiance is used to predict the heating and cooling requirements. The (time-varying) daylight illuminance is used to determine the electric lighting usage (which in turn is included in the heating/cooling calculation). The dynamic thermal response can be predicted for different construction types (e.g. light, medium and heavy) using the same set of DCMs. The only requirement is that the internal reflectivities are broadly similar as the daylight distribution (and therefore electing lighting usage) depends on this.

To summarise, with a single set of DCMs we can predict the energy requirements for heating, cooling and lighting for a specific building configuration in any climate zone, for any orientation and for a range of construction ‘weights’. This is indicated by the shaded area (i.e. Loops B and C) in the process flow chart (Figure 1). When the building configuration changes (e.g. different arrangement of shading devices), another set of DCMs must be computed, i.e. Loop A (Figure 1).

## **Building Scenario**

As stated previously, this study is focused on the analysis of low-tech non-domestic buildings. With this calculation scheme we can predict the annual energy consumption: electricity consumption due to artificial lighting and air conditioning (cooling) and natural gas due to heating. Later this will help us to determine the overall CO<sub>2</sub> emissions for different building scenarios in developing areas where a low-tech feature -such as an external shading device-can help to lower CO<sub>2</sub> emissions.

The *basecase* building used for this study is a 7m. by 7m. open plan office with a 2.7m height ceiling, and a window on one side of 7 m long by 1.10m high. The office was considered to be part of a larger office building, therefore all the internal walls were considered adiabatic for thermal purposes and only the wall including the window is facing the exterior and assumed to be built with ‘light’ building materials and single glazed.

Shading devices are created and applied to the basecase geometry. For this particular experiment a set of 8 different cases were tested (Figure 2).

- Basecase model (without shading)
- Horizontal shadings with parallel slats in different tilted angles (0, 15, 30, 45)
- Vertical shadings with parallel slats in different tilted angles (-45, 0, +45)

## **Irradiance and Illuminance predictions**

A grid of points act as ‘virtual’ photocells : one on the work-plane pointing upwards (36 points) for calculation of illuminance. This grid is 1 metre away from the walls and has one virtual photocell every metre. Another grid is parallel to the window plane at 0.05m inside, this grid has 100 points to predict irradiation behind the glazing plane. This grid covers only the window surface and it has virtual photocells pointing to the exterior every 0.35 m in horizontal and one in every 0.22m in vertical. On this point lies one of the originalities of this work while in most of the literature irradiation values come from less reliable assumptions or proportional calculations when solar radiation reaches shading devices. In this approach, irradiation is obtained explicit modelling of

radiation transfer from the source (sky + sun) to the photocell, including inter-reflection.

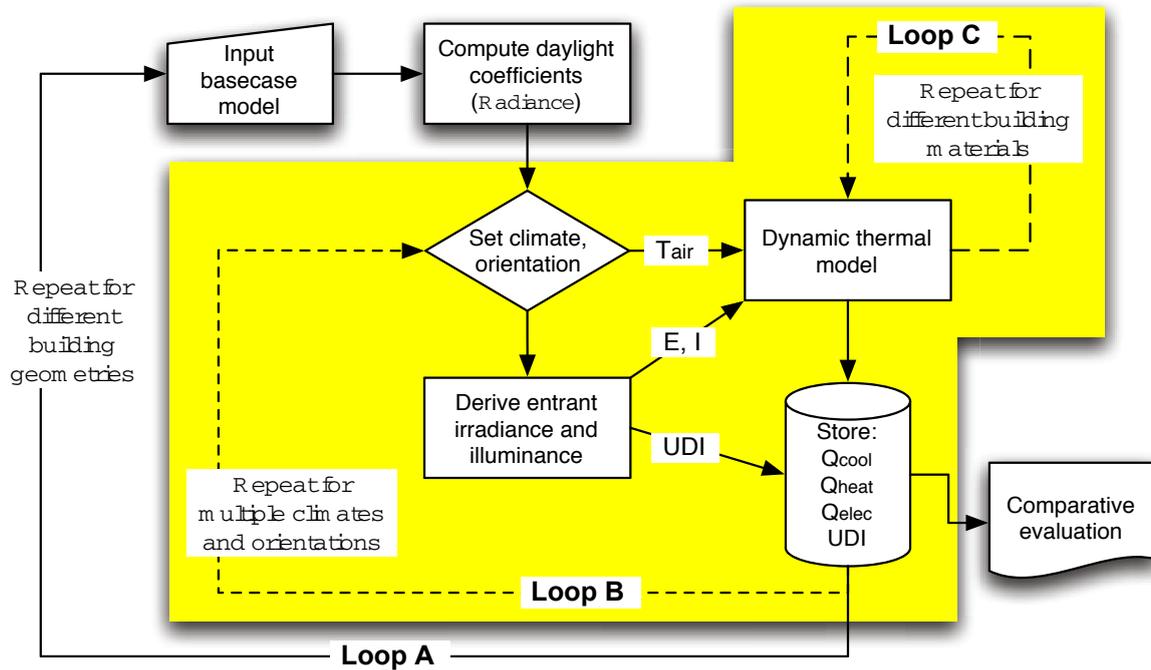


Figure 1. Flow chart of the calculation scheme

Irradiation values calculated by Radiance are used as inputs to both calculations: illuminance values on the working plane (through a luminous efficacy value) and irradiation on the window plane for the thermal model. This allows us to evaluate the performance of the window-shading device from a lighting and thermal point of view. Irradiation passing the shading device and glazing plane will become light across the working plane but also heat inside the room and therefore part of the loads for the air conditioning system.

As Daylighting Coefficient Matrices are specific to each shading configuration, these programs must be run as many times as geometries are under calculation. The custom-written programs can be modified to produce a comprehensive number of simulations covering all the parameters with the same run, therefore they are capable of analysing the whole study in a few minutes. Once DCs are calculated, a series of illuminance and irradiation values for different climates and orientations can easily be computed following the same kind of routines (Loop A in Figure 1).

The time-varying daylight and irradiance quantities are predicted using the refined daylight coefficient scheme devised by Mardaljevic [2000]. This was validated using the BRE-IDMP dataset and proven to be highly accurate [Mardaljevic, 2001].

In computational terms, the simulation time to generate the daylight coefficients is equivalent to 145 times that needed to carry out a standard daylight factor prediction. Thereafter, the derivation of hourly daylight (and irradiance) quantities for a full year is almost interactive (i.e. a few seconds).

When authors in the past have used *Radiance*, or other ray tracing programs, to generate incident irradiation time-series for input to thermal programs, the lighting simulation was in effect an auxiliary process that was secondary to the thermal modelling. Here we adopt a reverse approach: the daylighting/irradiation modelling comprises the larger simulation effort whilst the thermal modelling is essentially a rapid post-process that is called automatically. Thus the thermal modelling adds little computational overhead, and, more significantly, it permits the “scripted” (i.e. automated) evaluation of multiple scenarios.

### Dynamic thermal model

The thermal model follows a scheme, based on structural elements time constants given by the classical stores-to-transmitted energy ratio to calculate five parameters describing the thermal response for a single-zone building. The parameters describe the thermal mass of the building structure and of the air it contains, the heat loss/gain by thermal rapid response paths (ventilation, glazing, etc.), heat flow from the interior of the building to the thermal mass and from the thermal mass to the outside. Our Irradiance

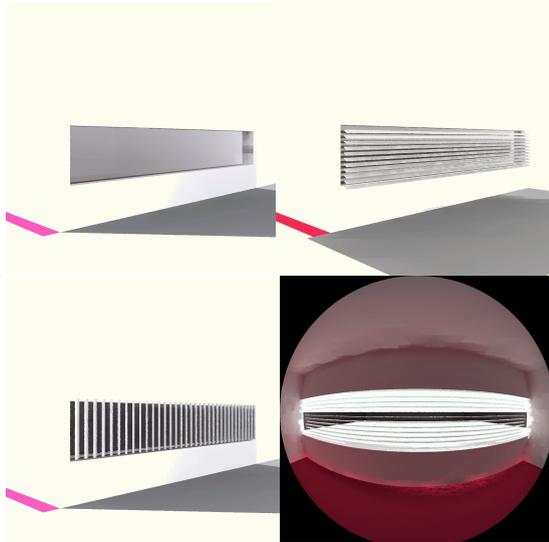


Figure 2. Top Left: Basic Case- Right: Horizontal sh.- Bottom Left: Vertical Sh- Right: Fish-eye inner view

predictions are used in this context as part of the solar gain calculation of the thermal model. The model takes in account the dynamic thermal response of the building and calculates heating and cooling loads [Crabb et al, 1987].

Predictions of Annual Energy Loads due to artificial lighting and air conditioning (heating and cooling) for each shading design 'scenario' can be calculated with comparable accuracy to many of the existing thermal programmes.

The expression 'scenario' is then counting for a wide range of possibilities in the design of a building i.e.: different building geometries (Loop A -Figure 1), multiple climates and orientations (Loop B-Figure 1) and different building materials (glazing, walls and partitions, etc.-Loop C-Figure 1) being climate, orientation and materials workable with no additional computational cost.

### Useful Daylighting illuminance

The evaluation of natural lighting performance has been a key issue since an accurate prediction of internal illuminances has been made possible through simulation. In this work we evaluated daylighting performance through UDI (Useful Daylight Illuminances). The concept of 'useful daylight illuminances' allows the simultaneous quantification of internal illuminance at calculation points along the depth of a side-lit space, it can describe daylight illuminance in a space rather than in a point. This concept privileges occurrences of illuminances values within an acceptable range for the tasks involved in offices. This acceptable range is related with the occupants response to daylight levels which have been registered in different surveys (100 to 2000 lux) [Vine

et al., 1998][Roche et al., 2000][Christoffersen, 2000]. Under the light of this concept and using hourly climate data -TRY/ TMY- each scenario, that is to say: each combination of the basic geometry with a particular shading device, climate and orientation can be analysed with the percentage of the year when the points considered meet that condition. This procedure does not add computational cost to the scheme (Loop B in Figure 1)

For this calculation, a simple manual switch on/off scheme was considered. The electric lighting with an output constant at 500 lux was modelled to be switched on at any hour when this level of illuminance was not achieved by natural lighting. The outcomes of this analysis (heat due to artificial lighting) have been used also in the thermal model as part of the internal gains (Figure 1). Another outcome to be studied at a later stage will be the potential benefit of daylight linked lighting controls.

### RESULTS

The results for the set of eight scenarios are presented for a selected climate:

Guangzhou, China [N+23.13;E113.32] <sup>1</sup>.

We start our analysis with the daylighting performance of the proposed designs. A comparison between the Useful Daylighting Illuminances<sup>2</sup> point by point and the Not-achieved UDI<sup>3</sup> was made for a South Facade of an unshaded window and a window with vertical shading at 45 degrees to the left (Figure 3).

The use of the standard UDI% concept would show us that these windows will achieve 75% and 60% of UDI for the unshaded and the vertical shading cases respectively.

The use of UDI% calculation in a 'point by point' basis instead of the whole space would allow us to analyse which areas are being problematic and maybe improved with changes in some of the parameters involve in the shading design.

The comparison between the performance of unshaded window indicates that, still with the proposed shading device, the illuminance values at some points of the grid are out of the proposed range for visual comfort (100-2000 lux).

Looking at the Not-achieved UDI (i.e. < 100 lux) it becomes clear that most of the points throughout the

---

1. Window side is left.  
 2. Notice that UDI have been calculated throughout all the room and not only at the 'core' of it.  
 3. Not- achieved UDI for those percentages below the minimum of the range 100 to 2000 lux.

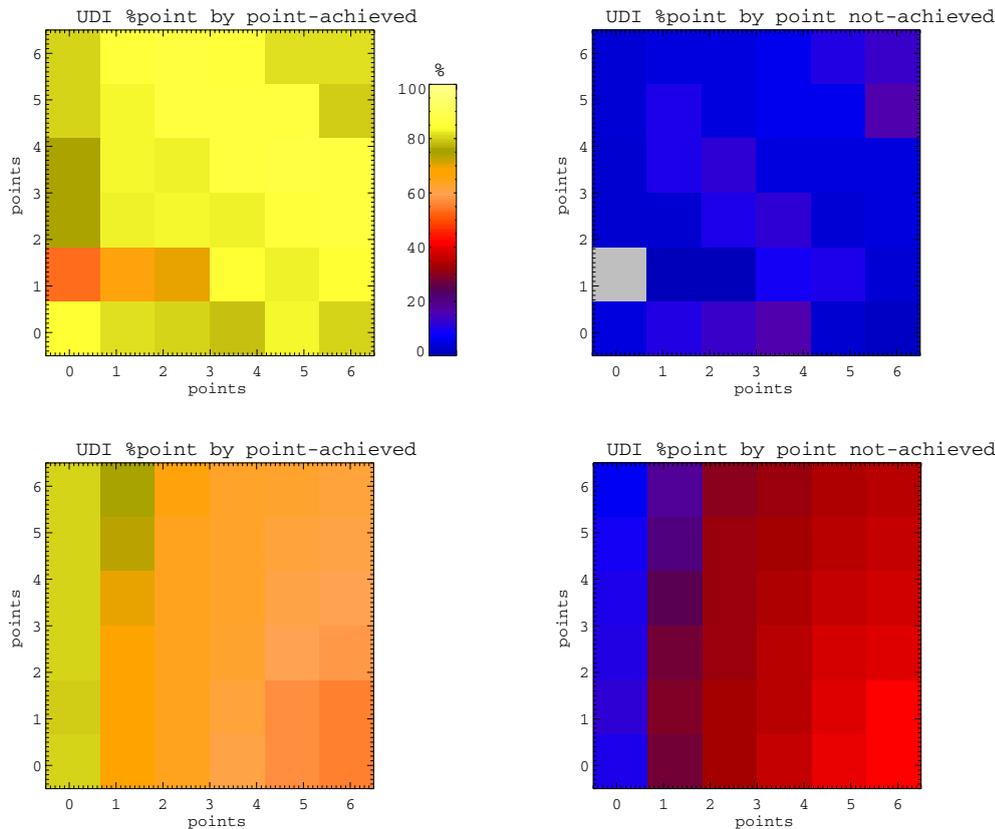


Figure 3. Top Left: Unshaded window UDI% values point by point- Top Right :Unshaded window Not-achieved UDI%- Bottom Left: Vertical Shadings UDI% values point by point- Bottom Right: Vertical Shading Not achieved UDI%

room will have an elevated percentage of high illuminances, this means that the electrical consumption due to artificial lighting would be low, nevertheless the influence in the thermal loads can be substantial.

The energy loads plot show a comparison between the performance of the selected scenario (Vertical -45) and the others within the established set of 8 (Figure 4). We can see that heating loads are not an issue for this particular climate, however the importance of the cooling loads is substantial.

If we use this loads to calculate the energy consumption using electricity for air conditioning (cooling) and natural gas for heating then we can also analyse the influence of each one of this energy consumption in terms of Carbon emissions because the annual total Carbon emissions will be the 'bottom line' of our comparison to know which decision is worth taking in environmental words [NEF, 2005][Van Vuuren et al., 2003] (Figure 5).

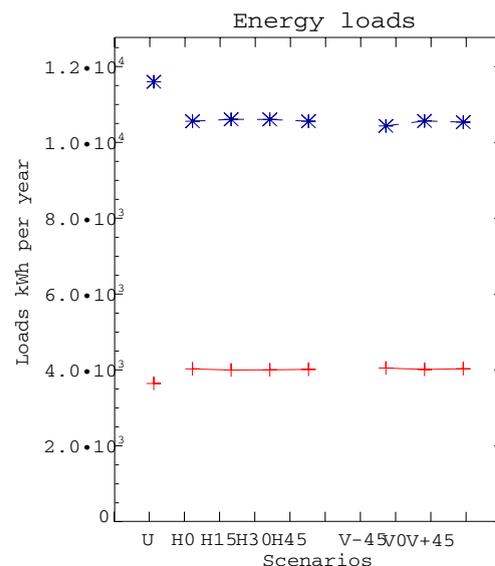


Figure 4. Energy loads for different shading for Guangzhou (China)- Cooling (\*) Heating (+)

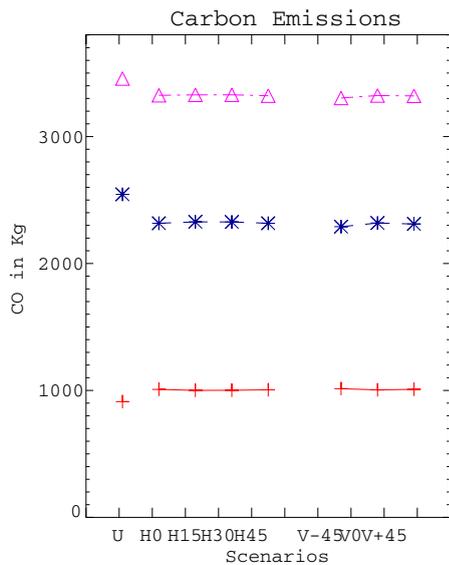


Figure 5. CO<sub>2</sub> Emissions for different shading for Guangzhou (China) Ref.: Cooling (\*) Heating (+) Total (Δ)

## CONCLUSIONS:

A novel hybridization of two dynamic building simulation techniques has been presented. Adopting this approach will help the optimization of external shading devices as it allows the generation and analysis of parametric studies. Hence the number of alternatives able to be studied multiplies the number of parameters considered in each of the loops of the scheme (Figure 1). Every particular geometry of shading device can be tested for multiple climates, orientations, glazing and building materials giving us the information of the daylighting performance, energy loads (cooling, heating, electric lighting) and carbon dioxide emissions associated.

There is no evidence in the literature on the application of a comparable approach to the problem of optimising the design of external shading devices.

Initially tested for “low tech” buildings and emphasizing the importance on geometry design decisions; it has still capability for analysing “high tech” building materials.

Even when this work is still in progress we can anticipate its great possibilities. For example: bringing *flexibility* to the forefront of the decision-making design process, *accuracy* in predictions based upon more ‘realistic’ and reliable data and *energy predictions* from each alternative under examination will place designers in preferable conditions to explore visual and thermal comfort alongside with Carbon emissions of their window-shading device designs.

## ACKNOWLEDGEMENTS

This work is funded by De Montfort University, Leicester, United Kingdom.

## REFERENCES:

- Cannon-Brookes (1997) “Simple scale models for daylighting design: Analysis of sources of error in illuminance prediction” International Journal of Lighting Research and Technology, Volume 29 Number 3 pp 135-142.
- Christoffersen, J.; Johnsen, K.; Petersen, E.; Valbjorn, O.; Hygge S. (2000). *Windows and daylight: A post occupancy evaluation of Danish offices*. Proc of Lighting 2000 Conference, 9-11 July, York, UK.
- Clarke, J.A. *Energy Simulation in Building Design* 2nd Edition, Butterworth-Heinemann (2001)
- Crabb, J; Murdoch, N.; Penman, J.(1987) “A simplified thermal response model” Building Services Engineer Research Technology Number 8 pp13-19.
- Herkel, S. (1997) “Dynamic link of light and thermal simulation: on the way to integrated planning tools” Proc. IBPSA Conference, Prague, Czech Republic, 1997, Vol II, pp 307-312.
- Janak, M. (1997) “Coupling building energy and lighting simulation” Proc. IBPSA Conference, Prague, Czech Republic, 1997, Vol II, pp 313-319.
- Janak, M. and McDonald I. (1999). ‘Current state-of-the-art of integrated thermal lighting simulation and future issues’ Proc. of Building Simulation ‘99 an IBPSA Conference. Kyoto, Japan
- Janak, M. (2003) “Whole building energy simulation with complex external shading devices” Proc. IBPSA Conference, Eindhoven, Netherlands, 2003, pp 571-576.
- Mardaljevic, J. (1998). *Advanced Daylighting Calculation, Rendering with RADIANCE: A practical tool for global illumination*. ACM SIGGRAPH’98, Course Notes CDROM, Orlando, USA.
- Mardaljevic, J. (2000a), *Daylight simulation: validation, sky models and daylight coefficients*. PhD Thesis. IESD De Montfort University, UK.
- Mardaljevic, J. (2000b) “Beyond Daylight Factor an example study using daylight coefficients” Proc CIBSE National Lighting Conference, York, UK, 2000, pp177-186.
- Mardaljevic, J. (2000c) *Simulation of annual daylighting profiles for internal illuminance* International Journal of Lighting Research and Technology, Volume 32 Number 3.
- Nabil, A. (2002) *Performance Modelling for Advanced envelope System*, PhD Thesis, IESD De Montfort University, UK

- Nabil, A. and Mardaljevic, J. (2005) “*Useful Daylight Illuminance: A new paradigm to Assess Daylight in Buildings*” International Journal of Lighting Research and Technology, Volume 37, Number 1, pp 41-59.
- National Energy Foundation (2005), CO2 Emissions Calculator based upon DEFRA data, Available at NEF Website: <http://www.natenergy.org.uk>, accessed February 2005
- Reinhart, C.; Walkenhorst, O. (2001) ‘*Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds*’. Energy and Buildings, Volume 33, pp 683-697.
- Roche, L.; Dewey, E. and Littlefair, P., (2000) ‘*Occupant Reaction to Daylight in Offices*’, International Journal of Lighting Research and Technology, Volume 32 Number 3.
- Tregenza, P.; Waters, I. (1983); *Daylight coefficients*, International Journal of Lighting Research and Technology, Volume 15, Number 2.
- Van Vuuren, D.; Fengqi, Z.; de Vries, B.; Kejun, J.; Graveland, C.; Li, Y. (2003) *Energy and emission scenarios for China in the 21st century*, International Journal of Energy Policy, Volume 31, pp 369-387.
- Vine, E.; Lee, E.; Clear, R.; Di Bartolomeo, D.; Selkowitz, S., (1998) ‘*Office Workers Response to an Automated Venetian Blind and Electric lighting system- A pilot study*’, Energy and Buildings, Volume 28, Issue 2, The international Council for Research and Innovation in Building and Construction.
- Winckelmann, F.C. (2001), ‘*Modelling Windows in Energy Plus*’, Proc. IBPSA Building Simulation 2001, Rio de Janeiro, September 2001.

