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# WHOLE BUILDING ENERGY SIMULATION WITH COMPLEX EXTERNAL SHADING DEVICES

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## ABSTRACT

In this paper an approach for pre-calculating building façade incident irradiance levels under a typical, yet computationally complex, external shading device with state-of-the-art ray tracing simulation techniques is presented. The impact of accurate modelling of direct solar, diffuse sky and inter-reflected irradiance components on resulting levels of thermal comfort and energy demand is analysed and recommendations are given for improvement of modelling capabilities.

## INTRODUCTION

Solar radiation is one of the most significant energy fluxes contributing to the thermal zone energy balance. Accurate modelling of this energy flow is of great importance in whole building energy simulation.

The typical approach involves the calculation of time dependent external surface shading coefficients, for which different algorithms have been implemented in different programs. The common factor is that these algorithms are relatively limited in their calculation capability. In general, the sky diffuse and inter-reflected components are not treated accurately and the calculation algorithm cannot handle the complexity of the solar radiation heat transfer mechanism (e.g. Clarke, 2001).

In this paper a summary of a short-term research study is presented. This study is concerned with a typical simulation-based impact assessment of an external shading device on thermal comfort and cooling energy demand in an office space.

## PROBLEM

The study is based on a simulation-based assessment of the influence of an external shading louvre array mounted in front of a transparent south facing office façade. Figure 1 shows an example of the modelled problem.

The louvres are mounted with 0.45 m vertical spacing. They have a rectangular cross section with variable depth from 0.2 m to 0.5 m and a height of 0.05 m.

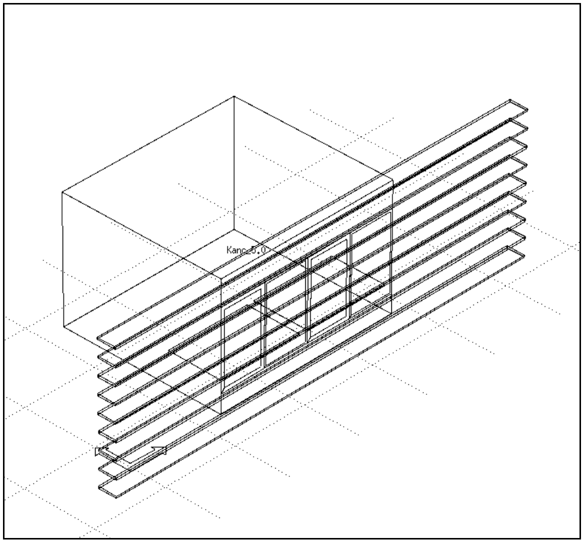


*Figure 1 An example of the studied problem geometry*

Although it may seem that the presented problem represents relatively simple geometry, it will be shown that the computational consequences are significant.

## APPROACH

In this study, the ESP-r whole building simulation program (Clarke, 2001) has been applied in its default mode with special features enabled such as an adaptive convection algorithm (Beausoleil-Morrison, 2000) and solar shading and insolation (Clarke, 2001).

In ESP-r's default approach, the direct solar component of the external surface irradiance is reduced using a pre-calculated database of time-varying shading coefficients. These coefficients are calculated for a typical day in the month (e.g. the 15th day), for each sun – up hour during the day and for selected external surfaces. The method of geometrical projection of shading obstruction blocks onto shaded surfaces from the sun position is used. Details can be found in (Clarke, 2001).

The surface irradiance from sky diffuse radiance is calculated according to the well-known Perez anisotropic model (Perez et al., 1990). The diffuse irradiance with ground reflected component is calculated with an isotropic ground condition model (see Clarke, 2001).

Unfortunately no attempt is made to account for the reduction in sky diffuse component and inter-reflected components (e.g. from ground and external shading surfaces) as a result of the presence of an external shading device.

The author believes that there is a good reason for this. It is a far from trivial task to formulate a comprehensive (while manageable) simulation-based method that is capable of accurately handling solar radiation transfer mechanisms (for at least a few types of solar shading devices available on the market). The situation is even more complex because of synergy effects between solar radiation and other heat transfer processes.

A good example of the underlying complex issues of this problem can be seen in a comprehensive research study published by (Kuhn et al., 2001). The approach adopted in this research is based on an experimental and computational determination of the solar altitude and azimuth dependent total solar energy transmittance (g-value).

Many interesting conclusions can be made based on results of this research. For example:

1. Results from experimental measurements are by their nature limited to the measured shading device type. It is impractical to cover all possible cases by measurements – a simulation approach is required to complement experiments.
2. A powerful forward ray tracing simulation program is needed to process complex shading devices. To the author's knowledge, Open Source or low cost optical software is not available to the building simulation community.
3. Is the g-value approach really the way forward in building energy simulation? While g-value is a useful parameter combining solar radiation and heat transfer effects, it is part of a component-based rather than a simulation-based approach - very much like the U-value concept. The author's opinion is that a step back into separate figures for transmitted, absorbed and reflected components for each thermally significant layer of a glazing system could give an opportunity for a reduced nodal model of the system. The nodal approach seems to be, in general, the way forward for building energy simulation.

Another good example is the WIS project (WIS) that has produced the publicly available program WIS for calculation of glazing system optical and thermal properties. In the WIS program a model of a shading device is included in an overall nodal model of the system with allowance made even for ventilated cavities. Although WIS has made a step forward in improving the accuracy of input data pre-processing for building energy simulation, its practical application is still limited by:

1. a shading device model that is currently limited to a flat and diffuse reflector;
2. the fact that the azimuth dependence of solar properties is not calculated.

As it is obvious that the default approach in ESP-r will introduce a clearly identifiable error in the amount of calculated irradiance incident on a shaded surface, an alternative method is needed.

Two approaches have been adopted. First, a relatively straightforward approach uses the WIS program to pre-calculate a set of angular dependent optical data (direct transmittance, absorptance in individual glazing layers and diffuse transmittance) that are used to model the overall glazing system with the shading device. The limitations are those of WIS model's capabilities to handle the complexity of the shading devices.

The second approach employs the global illumination ray tracing program Radiance (Radiance) to calculate the ratio between façade illuminance and global horizontal illuminance. This ratio is used to scale global horizontal irradiance to façade irradiance. The calculation is carried out for a grid of the points on the façade plane behind the shading device (see Figure 2).

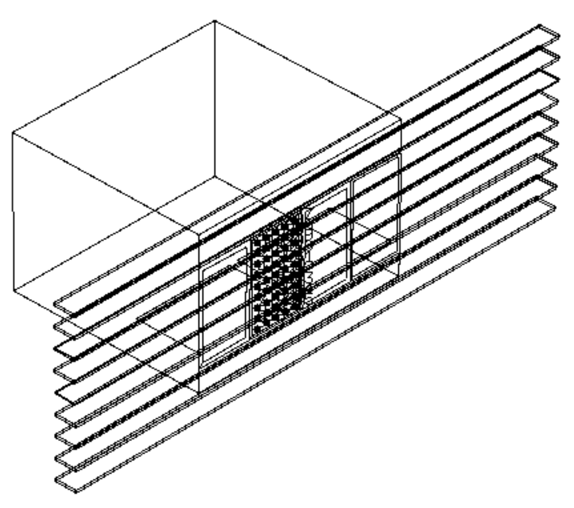


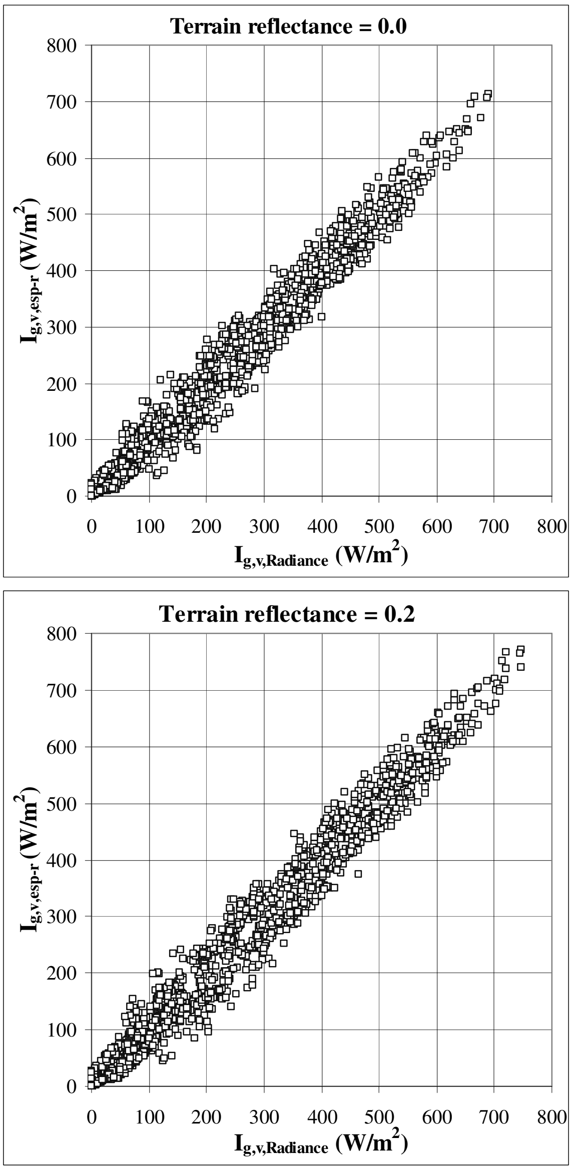
*Figure 2 Calculation grid points at the façade face (reduced number for display purposes)*

A mean value from all grid points is taken as the façade illuminance for scaling purposes. Such mean values are calculated on an hourly basis. The third party Radiance sky source generation program gendaylit (Gendaylit) is used for defining the sky luminance distribution model from standard irradiance data included in a climate file. This program uses the Perez luminance distribution model (Perez, 1993).

There is a question regarding the validity of the explicit assumption concerning the equality of illuminance and irradiance ratios used for scaling global horizontal values to global vertical values. Therefore an inter-model comparison is presented in the next section.

## BASE CASE

Figure 3 shows a comparison of the global vertical irradiance calculated by the ESP-r default method and by scaling from illuminance ratios without and with the ground reflected component for the unshaded case.


Terrain reflectance = 0.0

Terrain reflectance = 0.2

*Figure 3 Comparison of calculated global vertical irradiance by the ESP-r default and illuminance scaling methods*

Table 1 shows the mean bias error (MBE) and root mean square error (RMSE) between the ESP-r default method and the method using illuminance scaling ratios.

*Table 1*
*Error comparison between methods*

| Case | MBE | | RMSE | |
|---|---|---|---|---|
| | W/m$^2$ | % | W/m$^2$ | % |
| Terrain ref. = 0.0 | 1.51 | 1.5 | 31.9 | 16.3 |
| Terrain ref. = 0.2 | 1.78 | 1.6 | 35.8 | 16.3 |

The low MBE shows that both methods integrate into an identical energy content of the global vertical irradiance over the analysed period from May to September. The RMSE is at the level from 32 W/m$^2$ to 36 W/m$^2$ or around 16 %.

Figure 4 to Figure 7 show that there is a minimal difference in predicted parameters such as peak cooling load (Figure 4), cooling demand (Figure 5) and thermal comfort (Figure 6 and Figure 7) between the two methods for calculating the global vertical irradiance.

Based on the presented results it is possible to conclude that the method for calculation of global vertical irradiance with Radiance, based on illuminance ratios, is a valid engineering approach.

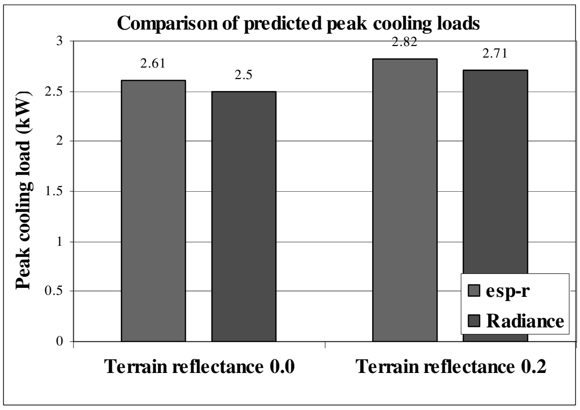

Comparison of predicted peak cooling loads

*Figure 4 Comparison of predicted peak cooling loads*

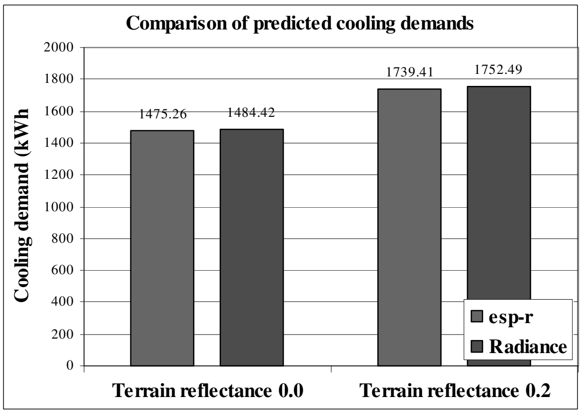

Comparison of predicted cooling demands

*Figure 5 Comparison of predicted cooling demands*

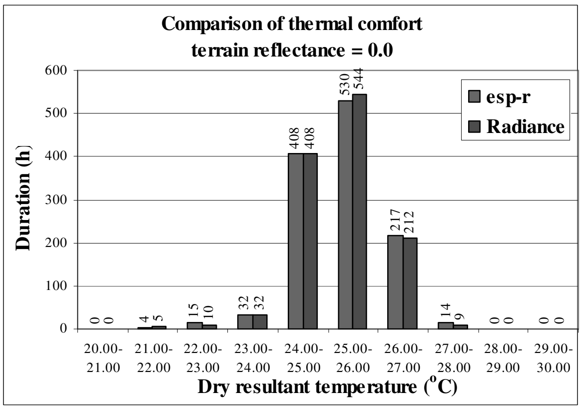


*Figure 6 Comparison of predicted thermal comfort*

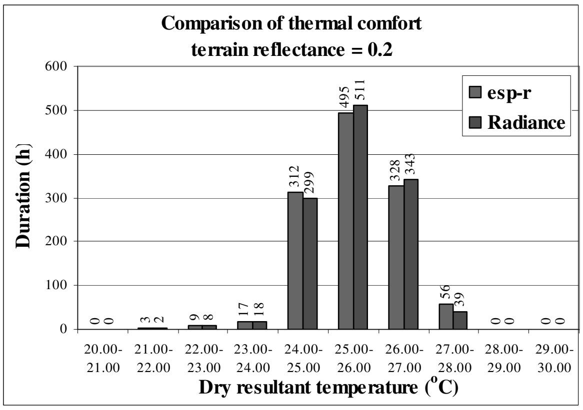


*Figure 7 Comparison of predicted thermal comfort*

## METHODS COMPARISON

Figure 8 and Figure 9 show a comparison of the calculated global vertical irradiance by the ESP-r default method and by the Radiance-calculated illuminance scaling ratios.

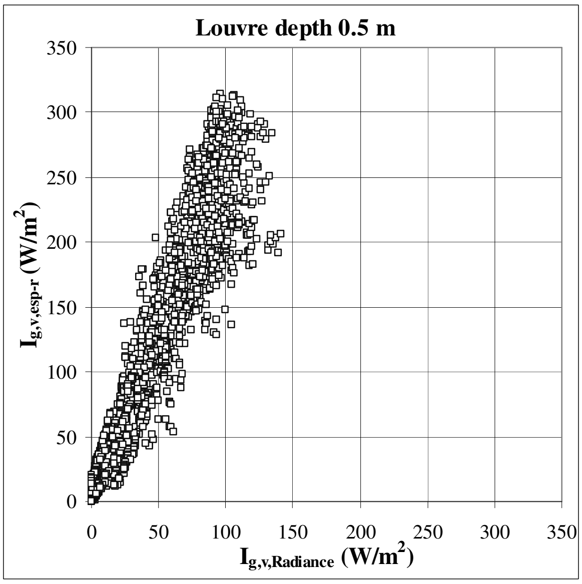


*Figure 8 Comparison of calculated global vertical irradiance by ESP-r default and illuminance scaling methods– louvre depth of 0.5 m*

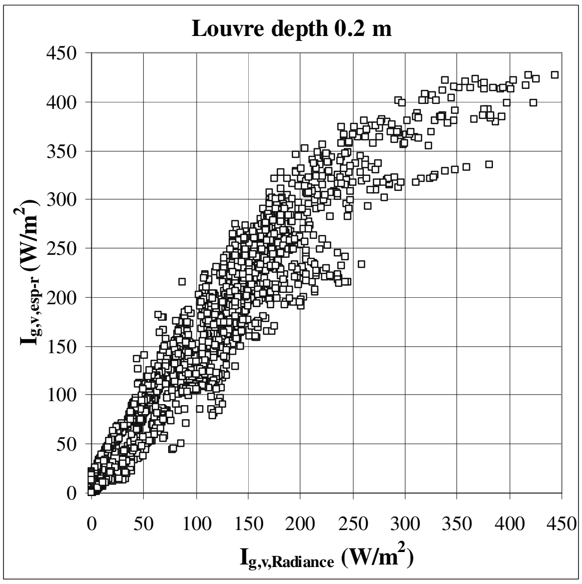


*Figure 9 Comparison of calculated global vertical irradiance by ESP-r default and illuminance scaling methods – louvre depth of 0.2 m*

Table 2 shows the errors between the ESP-r default method and the method using illuminance scaling ratios.

*Table 2*
*Error comparison between methods*

| Case | MBE | | RMSE | |
|---|---|---|---|---|
| | W/m$^2$ | % | W/m$^2$ | % |
| Louvre depth 0.2m | -40.6 | -29 | 54.7 | 42 |
| Louvre depth 0.5m | -77.4 | -59 | 95.8 | 62 |

The relatively large negative MBE shows clear over-prediction of the façade irradiance using the default method and the large RMSE indicates the significance of this effect. To assess the influence on simulation results, Figure 10 to Figure 13 show a comparison of the three methods (ESP-r default, Radiance and WIS) based on a range of predicted parameters.

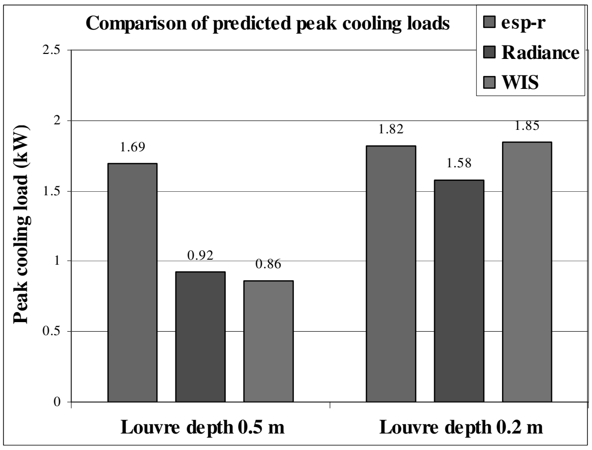


*Figure 10 Comparison of methods – peak cooling loads*

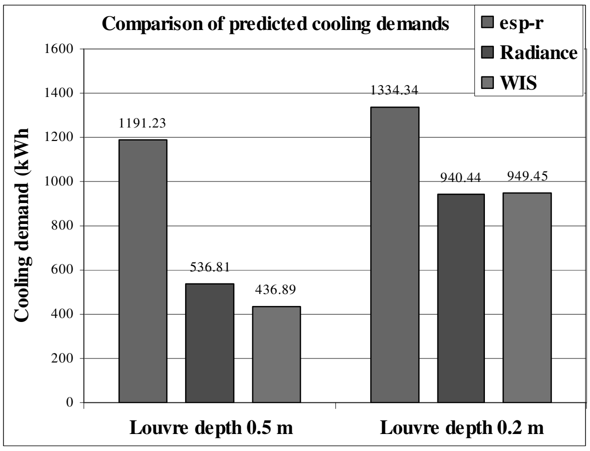


*Figure 11 Comparison of the methods – cooling demands*

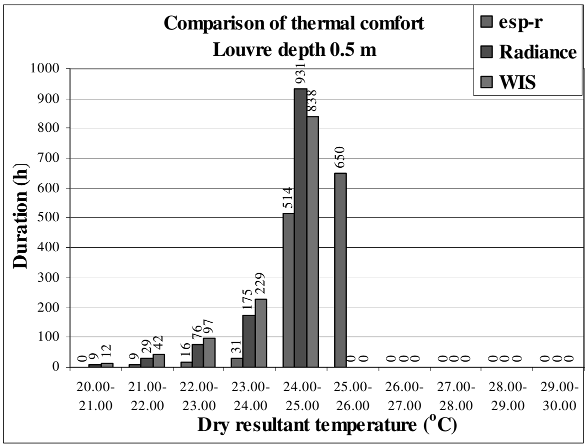


*Figure 12 Comparison of the methods – thermal comfort, louvre depth 0.5 m*

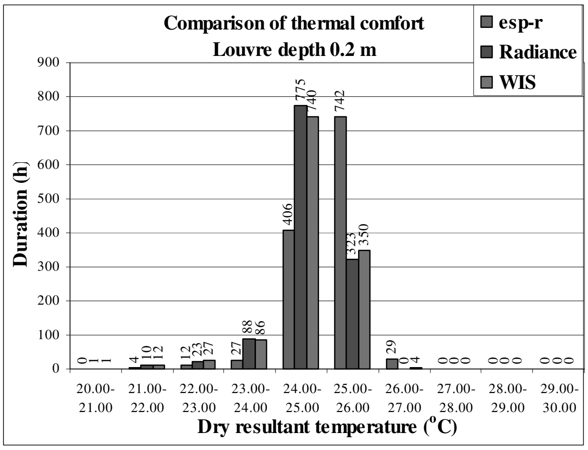


*Figure 13 Comparison of the methods – thermal comfort, louvre depth 0.2 m*

Table 3 shows the mean bias error (MBE) between the Radiance method and the other two methods. As can be seen from Table 3 and from simulation results presented in Figure 10 to Figure 13, the errors can be significant for the default method, which does not take account of the shading on the sky diffuse radiation and the inter-reflected components of solar irradiance.

*Table 3*
*Error comparison to the Radiance method*

| Case | MBE (%) | | | |
|---|---|---|---|---|
| | Peak load | | Demand | |
| | ESP-r | WIS | ESP-r | WIS |
| Louvre depth 0.5 | 84 | -7 | 122 | -19 |
| Louvre depth 0.2 | 15 | 17 | 42 | 1 |

On the other hand, the WIS approach produces results with relatively good accuracy when compared to the Radiance approach. There is a problem with peak cooling load overestimation by 17 % for the case with louvre depth of 0.2 m. This could be attributed to inadequate angular transmittance data resolution as held in the ESP-r database (0°, 40°, 55°, 70°, 80°) that does not capture the sharp decrease in direct solar transmittance at a particular angle. Azimuth dependence of this effect is also not included.

The good accuracy of the WIS approach is limited by the capability of the WIS shading device model. It would be easy to show that for shading devices with specular reflecting surfaces, errors would be large (see, for example, Kuhn, 2001).

## CONCLUSION

The presented method of illuminance ratios used for calculation of dynamic irradiance at the façade behind a shading device is more an ad hoc solution to a particular problem than a systematic approach. Its biggest limitation is that of the Radiance program (e.g. curved reflectors cannot be modelled) and a long computational time for complex cases. Its advantage is straightforward application and free availability of all tools used.

The recent developments in the area of time varying illuminance predictions (see, for example, Reinhard, 2000) make this approach available to wide building simulation community.

The problem of radiation, convection and conduction heat transfer modelling for complex glazing systems requires a systematic approach. This can be achieved using a nodal approach with pre-calculated angular absorptance at the individual nodes representing individual layers of the system. This approach is already implemented in, for example, ESP-r (Clarke, 2001). What is missing for the building simulation community is a powerful and affordable optical simulation environment capable of pre-calculating necessary angular (altitude and azimuth) data for the system.

Of course there are also other problems with radiative and convective heat transfer in these complex systems that should be tackled in the near future.

# ACKNOWLEDGMENT

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