COMPARISON OF COMPUTER AND MODEL SIMULATIONS OF A DAYLIT INTERIOR WITH REALITY

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ABSTRACT

The lighting simulation programme Radiance is used to predict daylight factors and the illuminance distribution in a room which is 12m x 12m x 3.6m high, with grey tinted solar control glazing. These predictions are compared with measurements taken simultaneously in the real room and in a physical model placed outside. Radiance is also used to predict the lighting conditions under a CIE overcast sky distribution. These latter predictions are compared to the predictions obtained by placing the physical model in a mirror box artificial sky.

Specific attention is paid to testing the accuracy of results, and the balance between computer calculation time and Radiance rendering settings.

Finally the computer model is used to explore the affect of adjusting light shelf finish. The relative contribution of view window beneath the light shelf and clerestory window above is also examined.

INTRODUCTION

As stated in "Daylight in Buildings" the brochure[1] that summarises the rationale of the IEA Task 21 project:

There seems to be some common barriers throughout the world, that hinder appropriate integration of the daylighting aspects (of building design). Three easily recognised barriers are:

- *Lack of knowledge on the performance of daylighting systems and lighting control strategies.*
- *Lack of appropriate and user friendly daylighting design tools.*
- *Lack of evidence of the advantages of daylighting.*

The main thrust of the IEA project is to endeavour to overcome these barriers.

This study focuses on one aspect of the second of these barriers: lack of appropriate and user friendly design tools. It compares two design tools; the traditional approach of making a physical model; and the approach that is currently receiving much research and development attention, electronic modelling using computer simulation.

This study uses Trad, the UNIX environment graphical user interface of Radiance, as a 'design tool'. Trad settings are documented to establish how designers may use Radiance to provide meaningful results in reasonable time when analysing the contribution daylight can make to the lighting of architectural scenes. Convergence tests are carried out by adjusting Trad settings then comparing results with the study room measurements and documenting the calculation time.

An extensive validation of Radiance's ability to model actual skies is currently being undertaken in the UK[2]. A sky scanner is being used to measure sky luminance distributions using CIE recommendations[3] which are then modelled in Radiance. Sky luminance distributions of this detail are not readily available. This study uses idealised mathematical distributions for the sky and as such the comparisons are an indication of the performance of electronic modelling combined with these idealised formula.

The ability of Radiance to model material properties such as specularity is also being investigated.

SIMULATION MODELS

Physical Modelling

Physical models, provided they are made to scale, provide accurate photometric results[4] and, subject to the model makers ability, provide true to scale representations of the proposed building. These models can be tested in many conditions. All types of sky from clear to overcast can be found if one places the model outside under a real sky. The position of the sun in the sky at different times of the year is conventionally modelled under a real sky by tilting and rotating the model building[5].

Artificial skies inside allow conditions to be controlled. This reduces the error that can occur due to the constantly changing nature of the real sky. The construction of the necessary equipment to simulate the sun and the sky indoors is, however, very expensive.

Physical modelling is a time consuming and costly process and is generally only viable once a building's architectural form is decided. Changes to evaluate new design ideas are not easy to make, which may reduce the use of models as tools to explore design alternatives. Physical models constructed either during conceptual design or as marketing tools are rarely made to the photometric accuracy necessary for the analysis of lighting and daylighting.

Electronic Modelling

Electronic modelling is beginning to replace physical modelling as a tool for visualising building concepts. However, as with physical modelling the final appearance of the product is often a representation which has no physical basis. The flow of light in the space is illustrative rather than realistic.

Recent advances in computer simulation and graphic techniques enable, in principle, the accurate physical modelling of interiors to produce realistic images and quantified photometric output.

Radiance is a rendering system that was developed at Lawrence Berkeley National Laboratories in California and Ecole Polytechnique Federale de Lausanne in Switzerland. It is described by its author Gregory J. Ward[6] as "a physically based rendering system ... which blends deterministic and stochastic ray-tracing techniques".

Radiance was used in this study for the following reasons:

1. It is able to handle complicated geometry.
2. Third party CAD translation package are available to create Radiance geometry files.
3. It supports a variety of reflection models.
4. It has the ability to model sky luminance distributions using mathematical models.

Radiance is not generally regarded as a user-friendly programme and it is used primarily in research. The large number of simulation variables is often daunting to the casual user and as a consequence it has not been widely accepted as a design tool in the commercial world. The graphical user interface of Radiance, Trad, was perhaps the first step towards making the programme more accessible whilst still allowing the seasoned user to customise rendering options. Adeline[7], a product of the IEA has reproduced many features of Radiance and Trad but within a DOS environment.

STUDY ROOM AND PHYSICAL MODEL DESCRIPTION

Study Room

The study room selected is located within the Schools of Architecture & Design building in Wellington. It is north facing and has the following features:

- Small amount of extraneous reflections from adjacent buildings.
- Little external shading by adjacent buildings.
- Sufficient features to check for correlation between models, e.g. Internal column creating shadow.
- North facing aspect so that the effects of direct sun and diffuse daylight penetration could be measured.
- A window opening designed to reduce solar gain. The glass is of the grey tinted solar control type (with a transmittance of 0.46[8]) and is approximately 250mm from the front of the structural opening with a 500mm deep overhang above.

An internal photograph of the study room, taken 21 July 1996, at approximately 10am is shown below in Figure 1.

Figure 1 Internal Photograph of Study Room

Physical Model

A scale of 1:20 was selected which resulted in a model approximately 600mm x 600mm x 150mm, large enough to allow the positioning of a light sensor and small enough not to create shadows when positioned within the artificial sky. The physical model was constructed using 5mm card/polystyrene sandwich board. Particular attention was paid to window, cill, overhang, side shading and window frame dimensions. Ceiling beams were also carefully represented as they would affect reflections at ceiling level.

Internal reflectances of the study room were measured using a Chroma Meter. These were then simulated within the physical model by applying paint of varying shades of grey in order to achieve reflectances which matched those of the coloured surfaces of the room. The floor of the model was carpeted with a remnant from the Study room. Measured internal reflectances were:

Table 1: Study Room **-** Measured Surface Reflectances

Room Surface	Refl	Room Surface	Refl
Kitchen Partition	64	Skirting	28
Blue wall	15	Beams	76
White wall	78	Ceiling	76
Columns	78	Door	6
Window shelf	22	Perimeter Heating	5.5
Window column	13	Floor	4.6
External surfaces	11	Rear Notice Board	48

The average reflectance of the room was approximately 0.45.

Figure 2 Internal Photograph of Physical Model

An internal photograph of the model is shown above in Figure 2. The photograph was taken within a photographic studio with diffuse lighting therefore little shadowing is present.

Physical model construction took approximately 24 hours

ELECTRONIC MODEL

Model Structure

A 3-dimensional model was created using AutoCAD Release 13[9] constructed entirely of 3-D faces[10]. Each face was sorted by reflectance into separate AutoCAD layers of unique colour then exported to Radiance using 'Torad'[11], an AutoCAD lisp[12] programme created in 1993 by Georg Mischler. As Torad does not recognise the solid modelling features of AutoCAD release 13, 3-D faces were used.

The resulting Radiance geometry and material files were identified by colour (they are assigned default AutoCAD layer colours during the export procedure). Each opaque surface was modelled using the Radiance 'plastic' description. The Radiance definition specified five material properties ie red, green and blue colour values (RGB), specularity and roughness. The window glass was modelled as Radiance 'glass' material with a transmittance of 0.46. As with the physical model, because only the reflectance of each surface was important and not its appearance, a grey scale rendering of the interior would have been acceptable. For example, a grey surface of reflectance 0.5 would be defined by its RGB values as 0.5, 0.5, 0.5. However to add 'realism' to the scene some surfaces were assigned colour, achieving the desired surface reflectance by adjusting the red(R), green(G) and blue(B) material descriptions using the following formula relating reflectance and specularity:

$$Refl. = Spec. + (1 - Spec.)(0.265R + 0.67G + 0.065B)$$

The ground and adjacent buildings, modelled as simple cubes, were assigned a reflectance of 0.2.

The electronic model took approximately 7 hours to construct.

Radiance Settings

The main user-controllable variables in Trad are the 'quality', 'variability', 'penumbra' and 'detail' settings and the number of indirect bounces (the rpict[13] -ab parameter).

The 'quality' setting affects the overall accuracy and beauty of the renderings produced. This study examined the effects of this setting using a varying number of indirect bounces.

'Variability' is a qualitative indication of how light varies in the scene. An artificially lit situation produces a fairly even distribution of light requiring a low setting whereas bright sunlight patches entering a room would indicate a high setting. The greater procesing effort of the high setting has a natural time cost. This project sought to determine what setting was necessary for accuracy.

As the study room was empty of furniture etc, a 'detail' setting of low was considered appropriate.

The 'penumbra' calculates for softer shadows from area sources when 'on' but in this study was left 'off'.

Time taken to render each scene was stored in a report file designated within Trad. Following the completion of each rendering the ambient file was deleted. The ambient file stores view-independent indirect irradiance values which are shared with further renderings of the same scene. This reduces the time taken to produce each future rendering and would therefore invalidate the results.

Computer simulations were carried out on a Sun Sparc20 60 MHZ computer with 96 Mb RAM.

Computer Sky Representation

Computer simulations were carried out using the sky as the only light source. The Radiance -av simulation parameter which controls the ambient light level was therefore set to zero, ie no ambient lighting. The -av parameter can be important when generating photo-quality images. Careful selection of this parameter introduces ambient lighting to 'fill in' any gaps that may be caused by the calculation procedure so producing a fuller image. This was not desirable in this particular study as any additional light added to the scene would effect the convergence test results.

Two Radiance programmes, both idealised mathematical functions, were used to approximate the sky's luminance distribution. The first programme, Gensky, uses the CIE overcast sky formula. It was used to generate the sky description for simulations of the physical model in the artificial sky and the study room in overcast conditions.

Gendaylit, based on the Perez[14] model, was used to simulate the sky description for simulating the model and study room under a real clear sky. This command generates a scene description of the sky using the Perez models for diffuse and direct components of solar radiation and irradiation. Perez concentrated on the development of a more realistic sky representation by basing the model on measurable parameters such as turbidity, sky clearness, sky brightness, cloud cover and percentage of clear sky. Consequently the sky luminance models encompass a range of sky types. The Perez model was developed using results from 13 sites in the northern hemisphere, ten in North America and three in Europe. It was assumed that these were representative of the New Zealand sky for the purposes of this study.

RESULTS

Measurements were taken across a 2m grid, 850mm above the floor, the first row 1m from the windows. Illuminance measurements were taken during two days, one clear and sunny, the other overcast. Simultaneous measurements were also made of external horizontal illuminance. Radiance results were generated to replicate these measurements. A typical rendering (Figure 3) shows luminance values (cd/m^2) at these positions. Figure 3 clearly shows the plan shape of the room.

Daylight factors are calculated at each point and then the average of each row is calculated. The resulting average daylight factors are shown in Figures 4-11. Physical model results are shown in figures 4 & 8 but omitted in other figures for clarity

Differences between actual measurements and calculated values are expected from a programme simulating a continuous luminance environment and therefore a near infinite number of light rays by

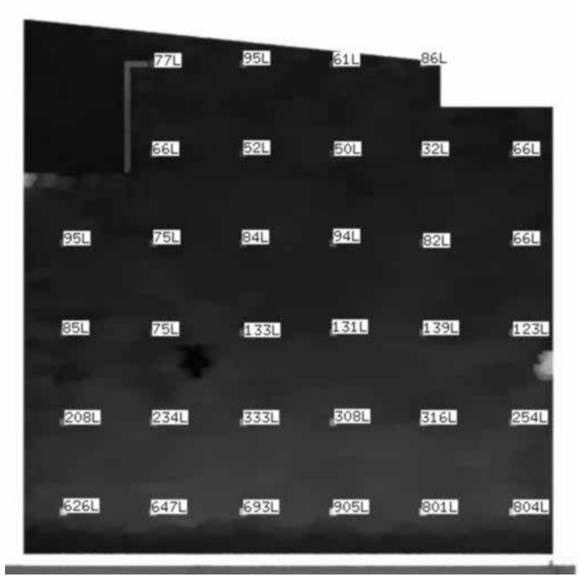

Figure 3 Radiance Plan View Rendering

approximating the behaviour of light within a scene. Figures 4-11 demonstrate that the number of indirect bounces and 'quality' settings have a significant role to play in the accuracy of simulation results.

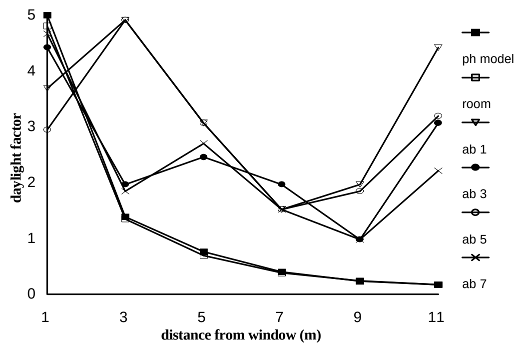

Figure 4 Radiance Settings - Low Quality, Low Variability Overcast Sky

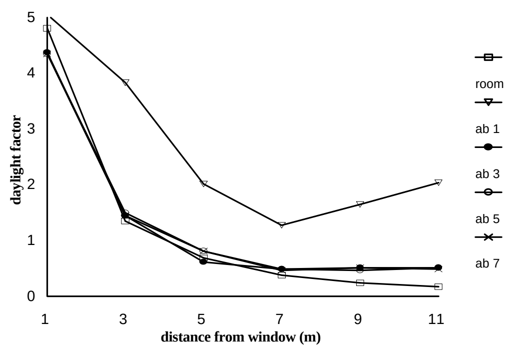

Figure 5 Radiance Settings - Medium Quality, Low Variability Overcast Sky

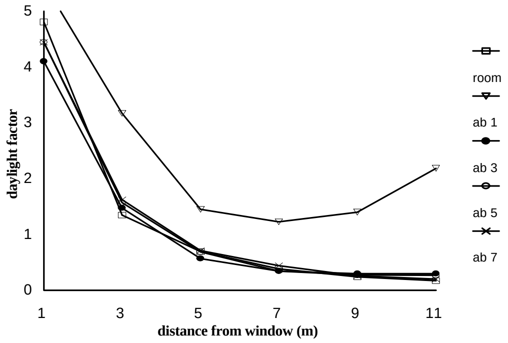

Figure 6 Radiance Settings - High Quality, Low Variability Overcast Sky

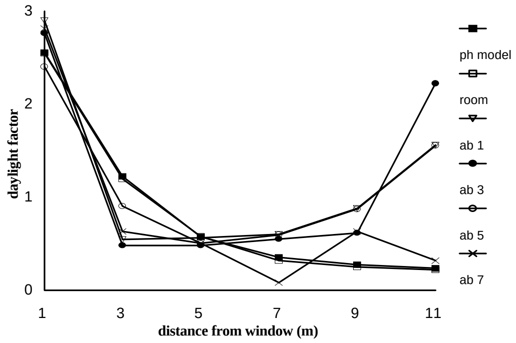

Figure 8 Radiance Settings - Low Quality, Low Variability Clear Sunny Sky

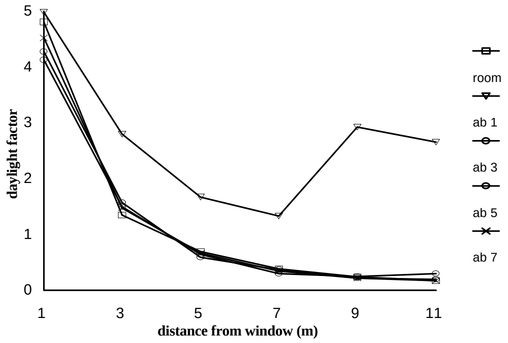

Figure 7 Radiance Settings - High Quality, Medium Variability Overcast Sky

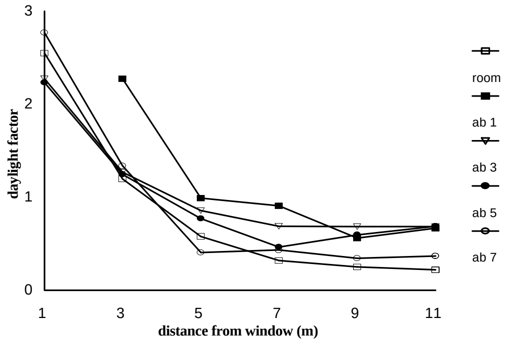

Figure 9 Radiance Settings - Medium Quality, Low Variability Clear Sunny Sky

Increases in the -ab or "quality" setting have a cost: they increase markedly the length of time the computer takes to complete the lighting simulation.

It can be seen that for overcast skies these settings have little effect on the accuracy of the results. The designer who is interested in quickly comparing several design alternatives can do so without compromising the accuracy of the results.

Comparing the results of figures 4-7 and 8-11 reveals that the influence of these settings is less important for simulations of the overcast situation. Representative results for overcast skies are provided by a medium 'quality' setting with 3 indirect bounces. More variation is exhibited by the clear sunny sky scenario where these settings play a more crucial role.

It is relatively easy to rationalise this modelling difference: the luminance contribution of an overcast sky of luminance 1500cd/m^2, would have reduced to approximately 2cd/m^2 after 7 bounces within a room of average reflectance of 0.45 with glazing of 0.46 transmittance. In comparison, the luminance contribution after 7 bounces from a clear sky of luminance 7000cd/m^2 would be reduced to 13cd/m^2,

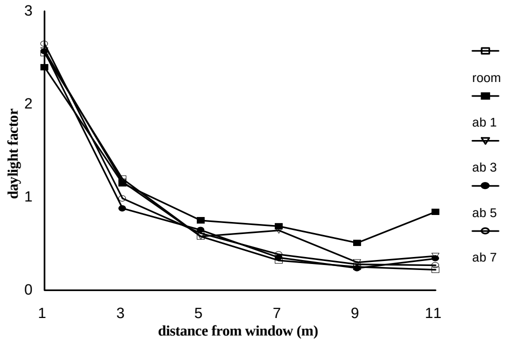

Figure 10 Radiance Settings - High Quality, Low Variability Clear Sunny Sky

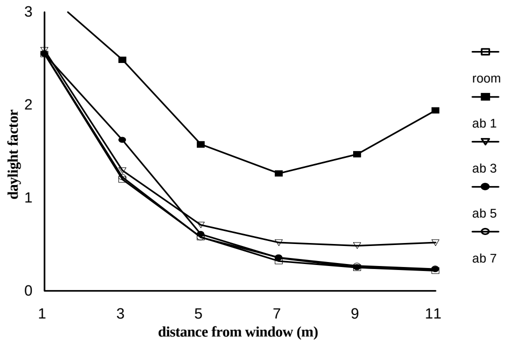

Figure 11 Radiance Settings - High Quality, Medium Variability Clear Sunny Sky

similar to that of the overcast condition after 5 bounces. In addition the sun's contribution would have reduced to 200cd/m^2 after 7 bounces, similar to the overcast condition after 1 bounce.

Figures 12 and 13 show the relative difference of prediction to actual measurement against the time taken to produce the rendering, for the various 'Trad' settings and number of indirect bounces. Relative difference is defined as:

$$RD = 100\ |(DF_{measured} - DF_{predicted})|\ / DF_{measured}\ ;$$

where DF is the daylight factor[15]

Both figures show that as the 'quality' setting and number of bounces increase when calculation times increase. Although low quality renderings were quickly produced in between 1 to 8 minutes for ab settings of 1-7 they produced relative differences too high to be shown in Figures 12 and 13.

The most accurate results occurred using high 'quality' and medium 'variability' settings but these had the longest calculation time. However these results were not significantly better than those produced by high 'quality' renderings with a low 'variability' setting once the number of bounces was set above 3 with results obtained in approximately one fifth of the time. If an accurate daylight distribution for such a scene is required there would appear to be little benefit in selecting a variability setting greater than low.

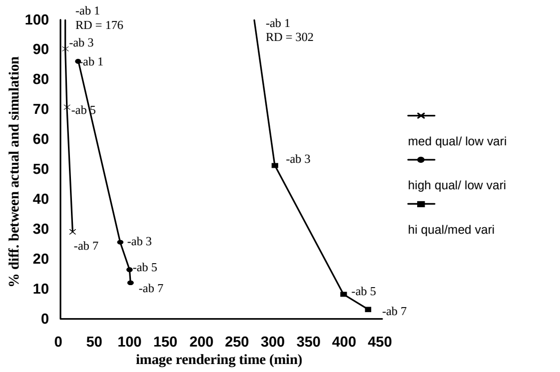

Figure 12 Time vs Difference - Clear Sunny Sky

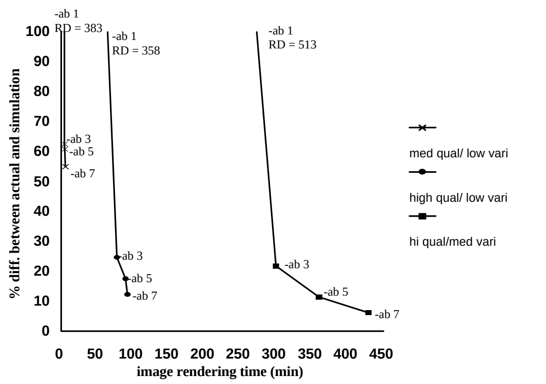

Figure 13 Time vs Difference - Overcast Sky

With 'quality' set at high and 'variability' at low, increasing the number of indirect bounces from 3 to 7 improved accuracy with little increase in calculation time (approximately 10 minutes). It would appear more beneficial therefore to increase the number of bounces with a 'quality' setting of high rather than improving the image by introducing medium or high variability.

A high 'quality', high 'variability' rendering with 5 ambient bounces was produced in approximately 26 hours. A high 'quality', high 'variability' setting was not fully tested.

An examination of the images produced reveals why some of the above results occur. Electronic images produced by Radiance were evaluated for quality, ie what the Radiance image looks like, and were compared against reality. The three images, shown in Figures 14-16, were produced using, firstly a low 'quality', low 'variability' setting, secondly a medium 'quality', low 'variability' setting and then high 'quality' with medium 'variability' settings. The -ab parameter was set to 5.

At first glance the low 'quality', low 'variability' image in Figure 14 is disconcertingly realistic. However, closer examination reveals why the relative difference

Figure 14 Internal Radiance Rendering - Low Quality

Figure 15 Internal Radiance Rendering - Medium Quality

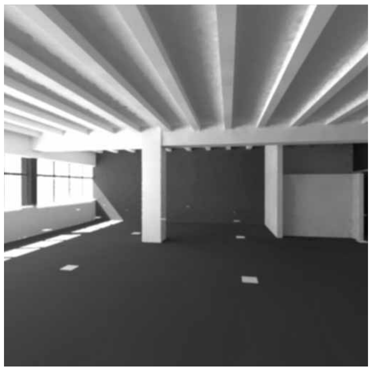

Figure 16 Internal Radiance Rendering - High Quality & Medium Variability

values in Figures 12 and 13 were off the scale for this simulation. In reality the side of the beams facing the windows would be ten times brighter than the sides facing away from the window. Discrepancies such as these are not present in the image generated using a medium 'quality', low 'variability' setting, Figure 15. This image looks less realistic than Figure 14. However, daylight factors calculated at each point, average the image faults such as the dark patches on the ceiling. It would appear the average large area luminance distribution is accurate. It is certainly of sufficient accuracy to assist design decision making for daylighting. However, for decision making based on appearance, and for assessment of glare potential in a scene, the image in Figure 16 is better. This was produced using high 'quality' medium 'variability' settings and took nearly five times as long to produce as Figure 15.

SIMULATION OF MATERIAL PROPERTIES

Radiance simulations of the scene and daylight calculations were repeated with light shelves added to the electronic model.

Radiance settings were set at high quality, medium variability with 7 indirect bounces, therefore a high accuracy would have been expected. Although physical model measurements were not taken, it was noted that the time taken to amend the computer model and analyse the results was approximately 2 person hours. To change the physical model would have taken approximately 10 person hours.

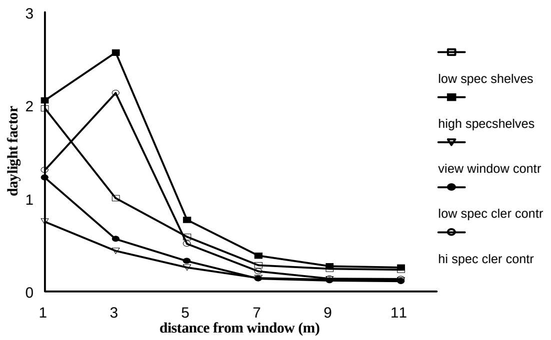

Figure 17 Typical Design Scenarios - Clear Sunny Sky

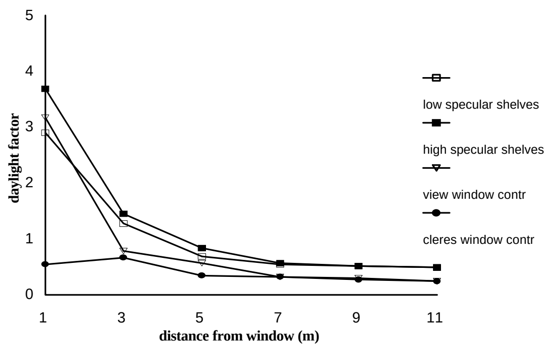

Figure 18 Typical Design Scenarios - Overcast Sky

Results are shown in Figures 17 & 18.

Daylight distribution for the overcast scene was not greatly effected by light shelf specularity. However the difference in results for the clear sunny scenario was significant. With high specular shelves the illumination 3m from the window was approximately 1½ times higher than when the simulation assumes a low light shelf specularity. In this case the major illumination source is the clerestory window above the light shelf.

CONCLUSIONS

The simulated results indicate that Radiance predictions of the internal lighting distribution under idealised sky distributions are highly dependent on rendering parameters. A high degree of correlation between predictions and measured results can be obtained.

The results suggest that acceptably accurate internal daylight distribution may be predicted by selecting a 'quality' setting of high, a 'variability' setting of low and 5-7 indirect bounces. If time is not of the essence other settings may be introduced such as 'variability' to improve accuracy.

If more photo-realistic images are required, it is not sufficient to rely on the 'quality' parameter without adjusting other settings. Figure 15 shows the discrepancies in detail that can occur. Figure 16 illustrates how this may be overcome by setting 'variability' to medium.

The choice of 'Trad' options available to the user are much fewer than those available when running Radiance from the command line. However even with the limited range of values offered the 'detail', 'variability', number of indirect bounces (0, 1, 2, 3, 4, & 5), quality and penumbra setting options produce a possible 324 choices. All have some effect on the lighting calculation. This study has not exhaustively tested all possible combinations to determine the ideal 'Trad' settings, however, it demonstrates that it is possible to get reasonable results within reasonable times.

Radiance is a lighting calculation tool. The images created on the computer screen are, in part, a by-product of the Radiance calculations. The 'realism' of the computer images generated was an unreliable indication of the degree of accuracy within the calculation process. Images which at first glance appear realistic can have quite inaccurate luminance distributions (Figure 14) but images with quite obvious flaws can be sufficiently accurate for daylight design decision making.

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8.Glazing transmittance was calculated by measuring the luminance of adjacent building facades both through the glass and directly with the window open. The transmittance was then calculated as the latter divided by the former.

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