A Comparative Study of Lighting Simulation Packages Suitable for use in Architectural Design

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Executive Summary

This comparative study is intended to present a guide to a range of computer-based simulation packages that are intended to provide an analysis of the lighting conditions in a building. The focus is both on the accuracy and the usability of the packages.

There is a wide range of packages that provide some of these capabilities (more or less), but there is little reported data that provides a reliable analysis for assessing their value or accuracy. In this report we are only able to report on those packages where we have some independent reviews, and where it is possible to compare the results obtained with a common or reliable point of reference.

In broad terms we can conclude that there is no ideal computer package, they all have their advantages and disadvantages. Having said that, it is possible to observe that there is one package that appears in most of the comparative studies and seems to offer reliable results in a wide range of circumstances. This is the RADIANCE package developed by Greg Ward Larson at the Lawrence Berkeley National Laboratory, Berkeley, California. This package is not directly accessible through a really good user interface (the ability to easily build and edit the models necessary to use the package), though there are signs that this problem is being overcome with some recent developments of plug-in/conversion modules for popular CAD packages.

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Contents

1 Introduction

1.1 Background Context

The need for buildings, in pre-historic times, arose from the necessity for shelter as evolutionary man moved from the cave. For much of the time since buildings have performed this primary shelter function. It is only relatively recently that buildings have become more expressive, or facilitating, of a wide range of lifestyle activities where the use of daylight (and even more recently artificial lighting) has played a significant role in both their form and function.

From early times a conflict in building design came from the need to maintain temperature (for warmth) and the lack of a building medium that allowed light penetration at the same time. This problem was solved with the invention of glass. Today the design conflicts are far more subtle, but probably no less significant.

We now have considerable flexibility to use both natural and artificial lighting in buildings. There is a full range of technologies which allow designers to create virtually any kind of internal environment, though there is still a wide range of design imponderables which test even the most experienced designers. Some of the key issues that confront today's building designer are:

- The efficient use of energy in the operation of the building environment that may be influenced by both regulatory/environmental and other social objectives.
- The comfort of the building occupants that may be influenced by health regulations and industrial/labour relations.
- Aesthetic and stylistic issues that accompany most aspects of the built environment.

There are many factors that impact on building performance, but central to most is the understanding and use of lighting (both natural and artificial) in the design process.

1.2 Lighting in Building Design

To many designers (still) the use of light in design is an "artistic skill" that cannot be simply expressed by a set of design standards or mathematical formulae. It is generally recognised that there are architects (the predominant designers of buildings beyond the domestic scale) who are able to craft their designs with light in much the same way as a painter uses oils, or a music composer uses sounds.

For most designers, however, some help and guidance is necessary. To this end there has been the development of a complete science of lighting that provides a formal description of the physical properties of light and the objects that reflect, absorb and transmit light. From this formal description we now have a wide range of design tools that allow all designers to meet most of the basic requirements for lighting in their designs (minimum levels for tasks, avoidance of glare, control of direct sun penetration and so on).

The physics of light is complex, and there are only a few that can fully understand its behaviour in the built environment. Hence the temptations that have emerged with the advent of computer technologies.

1.3 The Computer Revolution

On a superficial level the problem is simple. If we know something of the way that light behaves in a physical environment then why can’t we develop mathematical models that will show us what our building designs will look like before we actually build them? This question has been tempting for some time. Ever since the potential for computers to undertake large amounts of computation in short periods of time was recognised (the 1960’s), there has been interest in the development of computer-based models to predict what real objects will actually look like without building them first.

In the early days there was some promise, but this enthusiasm was dampened by the gradual recognition of the complexity of the task, the limitations of computer performance, as well as their cost. We now have much more powerful computers and some extremely sophisticated modelling packages that can (apparently) produce quite realistic images (just look at the current generation of computer games, or computer generated movies). The question we must now ask is: just how close are we to achieving our goals in effective modelling of light in the design of buildings?

One of the goals of this report is to explore some of the issues relating to this question. It is hoped that it will provide some background information that will enable a designer to make some informed judgements on the potential of the current state-of-the-art in computer prediction of lighting in buildings and how this may be used to assist in building design.

1.4 Foundations of Report

The work presented in this report is a compilation of already published materials. It is thus intended to provide a resource for the reader. The references included may have to be followed up by a reader wishing to learn more about the specific details of a topic or issue, or to evaluate a specific lighting simulation package.

The report does not include all the technical details which may form the basis of a particular topic in lighting, though a sufficient range of references are provided to allow the reader to locate more detailed or original sources.

The motivation for this report has come from the author’s involvement with Technical Committee TC3.33 of the Commission Internationale de L’Eclairage (CIE). This Technical Committee was concerned with performance of lighting simulation computer packages. The outcomes of their deliberations are presented here, together with other published work.

The interest of the report is broader that just the technical accuracy of computer packages, but also delves into the usability of these packages. That is, just how easy they are to use by a non-technical expert? There is very little formal analysis of the usability of lighting simulation packages. In an attempt to redress this lack of information the author circulated a questionnaire to about 20 persons within Australia and New Zealand in an attempt to provide some foundation information. Unfortunately this has not led to any really useful information, as there appears to be very few serious users lighting simulation packages in this region of the world. Only three responses were received which means that few quantitative conclusions can be reached. None-the-less some of the results are presented where it appears that the responses are consistent with the author's own experience and would probably not be contentious amongst independent reviewers.

Taking all the presented data together it is expected that the reader will gain some insights into both the accuracy and usability of a number of commonly used simulation packages.

2 Computer Simulation of Lighting in Buildings

2.1 The Theory

The basic physics of light in the built environment is reasonably well understood, though it is complex. A major part of this complexity comes from the issues of human perception of light. We know that light is basically electromagnetic radiation and it behaves according to the general rules for this radiation. Light is that part of the radiation spectrum which is visible to us through our eyes. This corresponds to wavelengths from 380 to 770 nanometres.

The complexity is added by the fact that our eyes are not equally sensitive over the full range of these wavelengths. In fact the eye's response follows a bell-shaped function. This means the response falls quickly at the extremes of the visible range of wavelengths. A rather good tutorial on the theory of light and its context as a part of electromagnetic radiation has been published by Ian Ashdown [Ashdown, 1996].

All light originates from light sources. Natural light comes from the sun (directly) and indirectly as it is reflected/refracted by water vapour and other particulate matter in the atmosphere. Artificial light comes from devices that generate electromagnetic radiation which is stimulated by the passage of an electric current (incandescent lights, fluorescent lights and so on) and to a lesser extent the combustion of some material (e.g. oil, gas). We can see objects in the real world as a result of the fact that for most objects a certain proportion of the light that incidents on their surface is reflected or refracted before it enters our eyes. This process causes some modification to the properties of the light (certain wavelengths are reflected preferentially and the amount of light reflected/refracted varies with the direction of reflection/refraction). As a result we see the full richness of the shape and colour of the real world we live in.

2.2 The Purpose

While most of us can see the results of an architect's work with light in the completed building, there is a great temptation to attempt to model this in advance. Predicting the outcomes may allow better design to be achieved or costly mistakes avoided..

There are in fact two related goals in this type of work:

- To produce a realistic visual representation of the design so an observer can visualize the appearance of the real building in advance. We will call this the *photorealistic* model. This model is for viewing.
- To produce a *photometric* model of the design that allows an accurate estimation of the properties of the light to be determined in advance. In such a model we are primarily interested in the intensity of the light, across the

visible spectrum of wavelengths, that is incident upon and reflected from surfaces in the scene. This model is intended to provide a quantitative understanding of the light.

In some ways, if the second model is done well, then it implies the first – but life is not a simple as that.

The photorealistic model dominates much of the computer graphics world where the goals are to create computer generated scenes that "look right". Such models are widely used in computer generated movies and from other computer graphics or visualization packages. These models can be very good, and look very realistic. A cursory examination may fail to distinguish the scene from a photograph of the real thing. The eye/brain system is a very cleaver piece of machinery, and will often overlook many inconsistencies or computational artefacts in the scene. On close examination it is common to find poor or missing representation of shadows, reflections and refractions. Overall, however, the model may be very effective and fulfil its purpose.

It is also not uncommon to find that the user must "tweak" a range of parameters to make the generated images "look right". This can include adding extra light sources, manipulating light source colours and adjusting material properties. This can be justified if the goal is to achieve the "best looking result".

The implications for this type of manipulation are that the physical properties of the light, and the scene being modelled, may not be related to the actual physical properties that we wish to measure. There is a danger of not being able to extract quantitative data from the models that would be of use to the designer who is required to meet particular design requirements (levels of light, etc). The photometric model is therefore required.

To resolve this problem we can attempt to develop a really good photometric model, then it should not be too difficult to construct a visualization of it that should look just like the real thing (if only it was so easy!). The problems we have are many, including:

- The optical properties of materials used in the built environment are complex and in many cases can only be approximated. We need to think specifically about how the material reflects/refracts light, both the quality and quantity of light.
- The passage of light (from several sources) in a scene before it ultimately enter our eyes is complex. There are many (infinite) pathways by which a single ray of light leaves its source, passes around and though the scene and eventually enters the eye. In practice we can only approximate these rays by a finite number for computational purposes. This often forces us to make great simplifications to the scene being modelled.
- The transformation of the results of these computations into a form that can be seen involves turning the numerical values into some visible medium (eg. coloured ink on paper, fluorescent spots on a CRT screen). This process is fraught with difficulties and generally requires some subjective adjustments[1].

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[1] Perhaps, in time, this information may be transmittable directly to the brain thus bypassing the need to use the eye/brain system.

Photometric models are often designed to meet some less ambitious objectives, perhaps to determine, with some reasonable level of accuracy, the properties of light in selected parts of the scene (a wall, a work surface, etc) that are critical to the design. In doing this, the computational task may be greatly simplified.

The point to be emphasised, however, is that if photorealism is the prime objective then some particular modelling approach may give the best results for the effort required, but this may not give access to sensible quantitative data about the light in the scene. On the other hand, if you are interested in specific photometric data then this should be matched to best method for getting it (at a cost) and this may not give you, as a by product, such a good visualization of the scene.

2.3 Model Building

The common use of CAD-based drafting (and other design) tools encourages us to believe that a single integrated model may be able to be used for several purposes (e.g. create the working drawings, prepare the schedule of quantities, undertake the thermal and lighting designs). This is still an ideal that is yet to be fully realized in practice.

The problems stem from the complexity of the data that is required to complete the various modelling tasks. Ideally the geometry model that might be used to construct the working drawings can be supplemented by lighting and material properties so that a lighting simulation could be performed. More often that not these tasks are only semi-integrated and it is necessary to export data from one package (the geometric model) and import it into the lighting simulation package. In practice this export/import process is not perfect with some aspects of the geometry being lost in the conversion, or additional properties are required to be added.

It is thus quite important to have a good understanding of the complexities of establishing the data for a lighting simulation and how well this is supported by your CAD package. There may be considerable work required to build the model for the lighting simulation package even though you already have a complete geometric model that generates the full set of working drawings for the design.

3 Overview of Selected Modelling Methods/Packages

3.1 Existing Packages

There is a wide range of existing packages that, to a greater or lesser extent, offer a capability to model the light in buildings. There is, however, a smaller number of actual algorithms and implementations, some of which appear in several different packages.

There are, however, two basic approaches to computing the distribution of light in a scene:

3.1.1 Ray Tracing

Ray tracing works on the principle of tracing all the light paths through the scene including reflections and refractions. We only need to trace those rays that are actually seen, i.e. those that end up in the eye, or at the viewing location. Since our view is projected onto a screen of some resolution it is only necessary to trace those rays that go through each pixel of the viewing plane to give an image at the same resolution as the viewing plane (e.g. CRT screen).

This is called backward tracing, as it traces light rays in reverse, i.e. from their destination to their source. Each ray must be traced through the 3D scene to a light source (or reflecting surface) and beyond if the surface is reflecting light.

Since there is a finite (but still perhaps large) number of pixels the computational task is manageable, but still can be significant. Decisions must be taken about how many internal reflections are allowed for in the computation.

The major problem with the basic ray tracing algorithms is that a new computation must be done for each viewing location. This adds considerably to the computational times if several viewing locations are required, or a "walk through" is being constructed.

3.1.2 Radiosity

Radiosity on the other hand is often the preferred choice where accurate photometric modelling is required. In this approach all the surfaces on the scene are subdivided into planar surface patches (generally triangles). The distribution of light is then computed iteratively by computing how much light is reflected from each surface patch onto each other surface patch. This requires a "visibility" calculation from each surface patch to every other surface patch, some of which will be light sources. Given a sufficient number of iterations, and a fine enough surface grid the results can be quite good. A comparison of a number of algorithms used for radiosity calculations is given by Wilmot and Heckbert [1997].

To give good photoreaslistic effects some surface interpolations must be applied (eg. Gouraud shading) and the choice of surface triangulations carefully made.

This approach offers a distinct advantage that the light computation is independent of view point, hence several views can be efficiently constructed after the main set of computations have been completed.

3.1.3 Which is Best

Ray tracing is possible the best choice to generate photorealistic images where the subtleties of specular reflections and refractions can be handled quite well. On the other hand radiosity is better for handling diffuse reflections and shadows.

In both cases there are decisions to be made about the accuracy of the calculation and the time required to compute the image. In theory both can produce good quality photorealistic and photometric images.

One of the most commonly used packages is RADIANCE [Ward Larson, 1995, Ward Larson and Shakespeare, 1998]. This package appears as the computational engine in a number of other applications. It in fact uses both ray tracing and radiosity in its computational model.

In either case, one should expect that the computational times will be significant – even with the speeds of modern PCs. There will be tradeoffs to be made with the accuracy of the models and these will be application specific, hence some experimentation will be required in parameter selection (number of internal reflections, triangulation size etc) as a part of this process. You cannot expect to get optimum results with one or two runs of the model.

Ashdown [1996] provides a summary of a number of available packages and their capabilities, though more will be available now. These can often be found by looking at the web sites of the major CAD package suppliers/vendors as well as searching the internet for lighting software packages.

4 Usability of Packages

The usability of computer packages is a complex concept. It clearly depends on the skills and knowledge of the user, though there may still be underlying usability issues that are more generic. Due to this complexity is it perhaps not too surprising that there is little published work on the useability of lighting simulation packages. To some extent this state of affairs is also supported by the fact that, in most cases, lighting simulation packages are complex to use (both in terms of data preparation and in operation) and that their use is largely restricted to "technical experts". We do, however, have some information on usability that is reported below.

When considering usability we will include the "quality" of the presentation of results. This will clearly impact on the photorealistic qualities of the outputs that, for many users, may be the primary interest.

4.1 Feature Comparison

Perhaps the most comprehensive review has been published by Ashmore and Richens [to appear, 2001]. This work reports a comparison of a range of desired features (both good and bad) of a simulation package. Their results (with some minor changes) are summarized below.

4.1.1 Output Features

Table 1 presents a summary of a range of features of a simulation package that would be useful in lighting design. Refer to the Appendix for a brief description of each of the packages mentioned.

These features refer to the ways in which the results of the computations are made available to the user, and hence how effective the user can judge if the results (for the given design) are acceptable, or otherwise.

4.1.2 Rendering Errors

Table 2 reports a comparison on a range of computational artefacts that may impact on the perceived quality of the appearance of an output image as also reported by Ashmore and Richens [to appear 2001].

Rendering errors arise when the computational model does not represent the real world with sufficient accuracy. Sometimes this is due to errors, or minor misalignments, in the geometric definitions. But, more often related to more subtle errors in the treatment of reflection/refraction processes. This type of error is likely to have more impact on photorealistic images where a "correct" visual result is required.

4.1.3 Comparison with the ideal package

Table 3 presents a set of attributes that have been put forward by Ashmore and Richens as being desirable in a simulation package, and the assessment of a number of packages against this ideal. The more ticks (✓) the better, and a cross (✗) indicates a less than satisfactory performance. A more detailed description of each of these attributes is included in the Appendix.

This ideal package reference is intended to meet most of the desirable properties in a simulation package. It thus provides a useful check list for assessing other packages. It should be remembered, however, that some of the issues raised may not be evident until you actually apply the package to your design problem.

Table 1: Comparison of Output Features
(● possible, ❍ with difficulty)

Feature	Adeline (Vers2.0NT)	Lightscape (Vers3.1.1)	Microstation (Vers7.1)	RadioRay (Vers2.0)
View of working plane with isoluminance contours	●	●	❍	❍
View of scene with isoluminance contours	●			
Renderings with surface coloured according to luminance	❍[2]		●	●
Renderings with surface colours according to illuminance			●	
Sample illuminance at a point	●	●	❍	❍
Sample luminance at a point.		●	●	
Photorealistic renderings	●	●	●	●
Quicktime Virtual Reality (QTVR)		●	●	
Virtual Reality Markup Language (VRML)		●		●
Walkthrough animation		●	●	●
Interior solar study animation			●	

Table 2: Comparison of observable errors in scene displayed
(more ● mean more errors)

Error Type	Adeline (Vers2.0NT)	Lightscape (Vers3.1.1)	Microstation (7.1)	RadioRay Vers2.0)
Mottling		●●	●●	●●
Light leaks		●	●	●
Shadow leaks		●●	●●	●
Unlit patches			●	●●
Mach banding			●●	●●
Shadow errors		●	●●	●
Colour casting				●●
Saturation	●●		●●	●●

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[2] This is apparently possible using the “false colour” option in ADELINE.

Table 3: Assessment of package against an ideal

The ideal rendering package	ADELINE (Vers2.0NT)	Lightscape Vers3.1.1)	Microstation (Vers7.1)	RadioRay (Vers2.0)
Photometrically correct				
Materials				
non-uniform BRDFs	✓	✗	✗	✗
refraction and transparency	✓	✗	✗	✗
specular to diffuse reflections	✓	✗	✗	✗
Model dimensions	✓	✓	✓	✓
variety of Sky models	✓	✓	✓	✓
chromatically correct	▪	▪	▪	▪
Quality of visual output				
common rendering errors				
Not mottled due to sky over sampling	✓	✗	✗	✗
No shadow leaks	✓✓	✗	✗	✗
No light leaks	✓✓	✓	✓	✓
No blocky shadows	✓	✓	✗	✗
No missing features (poor shadows)	✓	✗	✗	✗
No Mach bands	✓	✓	✗	✓
Interface				
Model geometry				
ease of import of models	✗✗	✓	✓	✓
portability of models	✗✗	✓	✗	✓
takes any model from any CAD system	✗	✗	✗	✗
light leaks and shadow leaks easy to fix.	✗	✗	✗	✗
accuracy of model	✓	✓	✓	✓
display of meshing	n.a.	✓✓	✗	✓
user control over meshing	n.a.	✓	✗	✓
Materials				
simple to understand and set up	✗	✓	✓	✓
materials Library	✓	✗	✓	✗
Cameras	✗✗	✓	✓	✓
Sky models	✓	✓	✓	✓

Lights	✗	✓	✓	✓
Empirical controls	✓	✓	✗	✗
stability	✗	✓	✓	✓
help/support				
online support	✗	✓	✓	✓
email / telephone support	✓	✓	✓	✓
threading	o.k	o.k	✗	✗
speed	✗	✗	✗	✗
Progress bars	✗	✗	✗	✗
Command line option	✓[3]	✗	✗	✗
Ease of setting up renderings	✓	✗	✗	✗
Display mapping	✓✓	✓✓	✓	✗
Output available				
photorealistic data				
bitmap images	✓	✓	✓	✓
VRML	✗	✓	✗	✓
QTVR	✗	✓	✓	✗
Solar study animations	✗	✗	✗	✓
walkthrough animations	✗	✓	✓	✓
photometric data				
illuminance / luminance contour plots	✓	✗	✗	✗
pick illuminance / luminance	✓	✓	✓	✓
use of working plane	✓	✓✓	✗	✗
display of values across a grid	✗	✓	✗	✗
automatic calculation of DFs	✗	✗	✗	✗
max/min DF and fraction above given %	✗	✗	✗	✗
customisable user interface.	✗	✗	✗	✗
Standalone v. integrated renderers	integrated system	stand alone	integrated system	plugin
Network rendering	✗	✓	✗	✗
	ADELINE (Vers2.0NT)	Lightscape (Vers3.1.1)	Microstation (Vers7.1)	RadioRay (Vers2.0)

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[3] Can be done by directly accessing RADIANCE, but not through the Adeline user interface.

4.2 Ease of Use

This is probably one of the most important aspects of any computer package. Given the rapid advances in user interface design (and capabilities) users expect to have a really slick user interface to work with. Formal assessment of the user interface is, however, a difficult task and there is little formal data available. As mentioned earlier the author did attempt a survey that could have provided some information, but the response rate was too small to be useful. We do, however, have some information, including anecdotal, that is perhaps worthwhile to present.

The two key problem areas are:

- The time taken to prepare, and edit, the data describing the geometry and optical properties of the scene.
- The time taken to run the simulations.

These two problems are related by the fact that the more accurate we make the scene the more effort is required to prepare the data. For complex models the computational times may also become excessive.

The ideal situation is where we can take the CAD model that might be generated for the physical design of a building, and use it directly for the lighting simulation. In general this is not possible, though some packages allow the import of CAD models (especially DXF files from a CAD package like Autocad) to define most of the geometry. There is still generally a lot of work to do to define the required geometry for the lighting simulation as well as the optical properties of the surfaces in the scene.

Building the 3D scene is a complex task, involving several iterations before a satisfactory result is achieved. The underlying problems arise from the required experimentation with the detail in the scene geometry. It is not always clear in advance to know what geometry detail must be included to achieve a useful result. Due to the considerable computational times it is often (always?) necessary to simplify the geometry definitions (to keep computational times manageable).

Some packages like RADIANCE (Unix version) provide little support for the user and the scene definitions must be prepared manually. This process is complex and tedious, though clearly optimised to the needs of RADIANCE (which is generally considered to be the best simulation package). The Adeline version of RADIANCE has a 3D modeller interface for building the geometry model and its optical properties, but it is clear that this interface (the Scribe modeller) is not very easy to use. There are some conversion packages available (e.g. Desktop Radiance, Rayfront, Radout, Torad, RADTOOL)[4] each of which provide some level of capability to prepare RADIANCE input files from CAD (most often, Autocad) design models.

It is perhaps reasonable to conclude that the community of users may well be waiting for a really good 3D modeller designed specifically for the Radiance package. This would provide a worthwhile contribution towards the needs of the lighting designer. The Desktop Radiance package appears to offer some potential, though it requires AutoCad R14 as a base package and is thus not free (as the RADIANCE package is). Support for other CAD packages is proposed.

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[4] A range of translators, converters and plug-ins for Autocad are available for RADIANCE. A number of these can be found from the Radiance web site: http://radsite.lbl.gov

There is also another line of argument that the fully-fledged simulation package will always be too complex to the average user (i.e. the non computer expert). This approach suggests that it might be better to "pre-package" geometry models, and their lighting properties, into design guides which can be more easily applied by the non-technical user. These packages fall into the class of packages called "expert systems" where the user is asked to describe the design/geometry context and through a system of look-up tables and rules, quantitative estimates of lighting levels can be provided. A recent innovation in this area is the LESO-DIAL package. In this case the user is required to choose a set of parameter values, and the model provides the estimates – based on prior calculations of similar situations and a lexicon of case studies. Providing the designer is dealing with simple/common cases this approach may well produce quite effective results. You cannot expect to get the photorealistic presentations for a particular design case, but the LESO-DIAL lexicon does contain images for the design cases/examples which may well be adequate in some cases.

Extending this concept further, if we have simple design tasks (e.g simple room geometries like "shoe box" shaped rooms with simple window systems) then the geometric modelling can often be simplified. The Superlite package is more suited to this type of context, and thus has a simpler geometric modelling process – though naturally with limited complexity. Adeline also provides a "simple input mode" which provides the user with a much simplified (though necessarily restricted) task of model building. Such approaches may be very effective where the building/room geometry is simple – though they will probably not result in photorealistic images of the scene.

5 Comparison of Selected Packages for Photometric Accuracy

5.1 Introduction

In an ideal world we would like to be able to provide some direct quantitative evidence about the accuracy the predictions of illuminance/luminance levels from various computer packages. The task is rather more complex than might first appear. If we aim to estimate the lighting properties inside actual building spaces, then there are many problems to overcome. These relate mainly to the optical properties of the light sources and the objects (their surface properties) in the scene.

Light sources will generally be some combination of the sky and the interior artificial lights. The luminance properties of luminaires can be measured and described mathematically with some level of accuracy, though the aging behaviour (light properties change with use/age) is more uncertain. Properties of luminaires are generally published by manufacturers and can be modelled inside simulation packages. Some light sources can be modelled as point sources (i.e. all light emanating from a single point), while others must be considered as line or area sources. These are typically more difficult to model.

Formal modelling of the sky is another problem. The sky not only changes dynamically but also naturally varies with location (location on the earth, and with climatic/atmospheric conditions). It is common to use one of the standard sky luminance models (the CIE models) but these, in most cases, provide an approximation to the actual condition at given location and point in time. A more detailed examination of sky luminance models is provided in a later section of this report.

Another problem area concerns the optical properties of the surfaces that define the objects in the scene. The scene is visible due to the passage of light through and around the scene caused by the absorption, reflection and refraction of light at every surface. To accurately model the scene appropriate optical properties for each material must be defined.

The reflective (both diffusing and specular) and refractive properties describe how a surface in the scene is seen. These will naturally vary with the direction of the incident light, its intensity, its colour as well as the optical properties of the surface. Reflected light is generally considered to have two components: a specular component that is the "mirror" like reflections, and a diffuse component that is the "scattered" light component. Both must be modelled.

Objects in the scene that are transparent to light will cause the light to be refracted as it passes through them. Glazed windows and internal partitions are of this type and their properties must also be modelled.

All these properties must be known accurately if the simulation is to be reliable.

5.2 Validation Strategies

The task of validating a simulation package requires some point of reference. There are several strategies, as discussed below, each with their own problems. It is important to understand the basis of the comparisons, as this will have some bearing on how the evaluations are to be assessed.

5.2.1 Mathematical Model Reference

This is perhaps the ideal case where we can construct a pure mathematical model of the building and generate analytically the luminance properties of every surface in the scene. Apart from the difficulty of defining all the light-source and surface material properties the problem is horribly complex. Except for some very simple scenes (e.g. a single rectangular box-shaped room) they are generally considered to be intractable. This type of approach is still important as it provides a first level of validation for a simulation package.

5.2.2 Real Building Reference

This is also a good way of validating a simulation package, as it may be able to show that the computer model can match the recorded measurements in the actual scene. The problems arise from the difficulties in matching luminaire properties (i.e. we may need to measure the properties of every light source) as well as the sky luminance properties (if natural light sources are present). Considerable effort will also be required to match (measure) the surface material properties of all objects in the scene.

The geometric properties of real scenes can also be very complex, often well beyond the labour and computational resources that we can afford to apply. In most cases simplifications have to be made and these may impact on the potential accuracy of the simulation model.

5.2.3 Scale Model Building Reference

A common approach concerns the building of a scale model of the building and undertaking measurements of illuminance inside the model with the model being placed in an “artificial model sky”. Often architectural models are built for a range of design purposes (especially visualizing the design) so, with some extra attention to model the optical properties of the surfaces of the objects in the scene, it is possible to measure luminance levels throughout the spaces of the building. The artificial sky provides the primary lighting source and is supplied by a collection of artificial lights, mirrors, etc to approximate the luminance distribution of a “real” sky. Naturally the accuracy of the sky luminance distribution is also important in achieving the correct illuminance characteristics inside the model.

Model buildings probably do not provide a useful vehicle for modelling the effects of luminaires due to the difficulty in modelling them at the scale of the building model.

5.2.4 Other Package Reference

If we can assume that we have one “correct” simulation package then it is possible to use this as a benchmark for other packages. This is, in fact, the most realistic approach to validation.

Unfortunately we do not have the absolutely “correct” package, but we are perhaps coming closer to agreeing on some good quality benchmarks. The results presented in this report will demonstrate some of these packages. It is probable that as simulation packages improve we will be able to come to rely on a small number of proven ones as good points of reference.

5.3 Some Validation Results

In this section we will present a range of results already reported on the comparison/accuracy of lighting simulation packages. The work is based on various of the above reference strategies. The results cover a range of experimental procedures and application domains, so there cannot be a simple solution to “which is best”, but the results will give us some good indications of the plusses and minuses.

The first group of results has been obtained from a recent, and comprehensive, study of several of the most commonly used simulation packages. This work was carried under the auspices of the International Energy Agency, Solar Heating and Cooling Program, Task 21, [Fontoynont et al, 1999]. This work probably represents the most thorough and systematic comparison work so far attempted. In most of these cases a scale model was used together with a range of computer-packages. The reader is referred to that report for more details of the study and a discussion of the results. Only a summary is presented here.

5.3.1 BRE Scale Model Tests on Simple Atrium

These tests involved the modelling of a simple 12.125m square atrium. The atrium is square in plan, with a horizontal glazed roof and the illuminance measurements taken at different levels (each of 3.50m height) in the atrium on the horizontal plane. See Fig 1. This is a very simple model and does not really test the simulation packages to any significant extent.

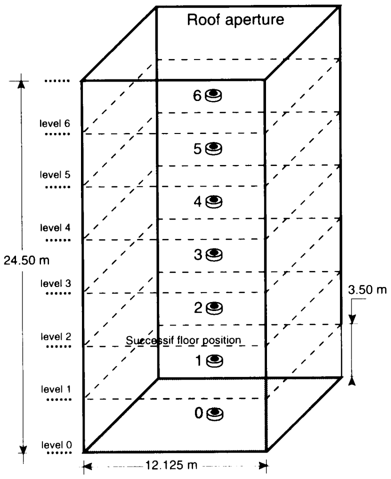

Figure 1: The BRE Model Atrium

The scale model measurements were carried at the Building Research Establishment (BRE) in the United Kingdom. Four different simulation packages were evaluated, Superlite, Genelux, Adeline and LESO-DIAL[5]. Note that Adeline uses the RADIANCE engine for its computations and that LESO-DIAL uses a pre-calculated look-up table (lexicon) to provide values.

The cases examined involved four different indoor wall surface reflectances, Black 5%, Dark Grey 30%, Light Grey 48% and White 85% (assumed to be perfectly diffusing surfaces). The lighting source was taken to be a CIE standard overcast sky, and the measurements and computations are expressed as daylight factors.

The comparisons are summarized in Figures 2 to 5. This example is quite a simple problem, the lighting conditions are well defined (CIE standard overcast sky) and the geometry easily described. The sampling point is located in the middle of the (adjustable) floor of the atrium at each level.

Figures 2 to 5 hence show a relatively good comparison between the four simulation models and the scale model measurements. If we take the BRE scale model as the reference case, we are achieving differences generally less than 5%. The differences tend to increase with the reflectivity of the wall surfaces in the atrium, i.e. impact of reflected light in the model. This is to be expected as the process for handling 2, 3 and subsequent, reflections deeper into the atrium is likely to put more stress on the computer-based models.

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[5] A brief description of the computer packages are provided in the Appendix.

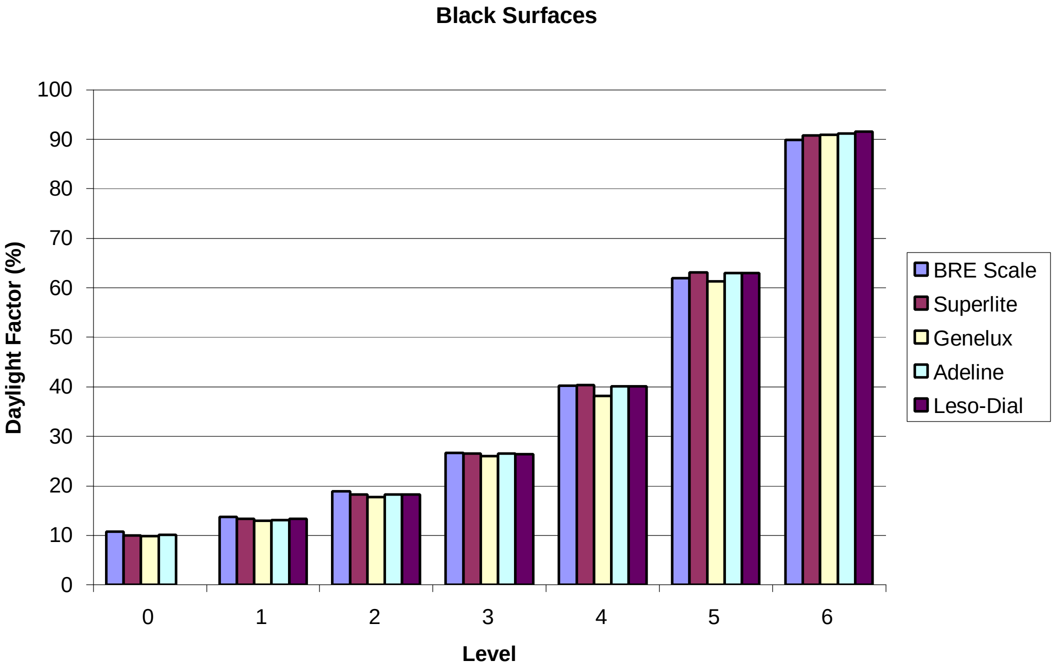

Figure 2: Comparison of results for BRE scale model tests on simple atrium for Black Surfaces

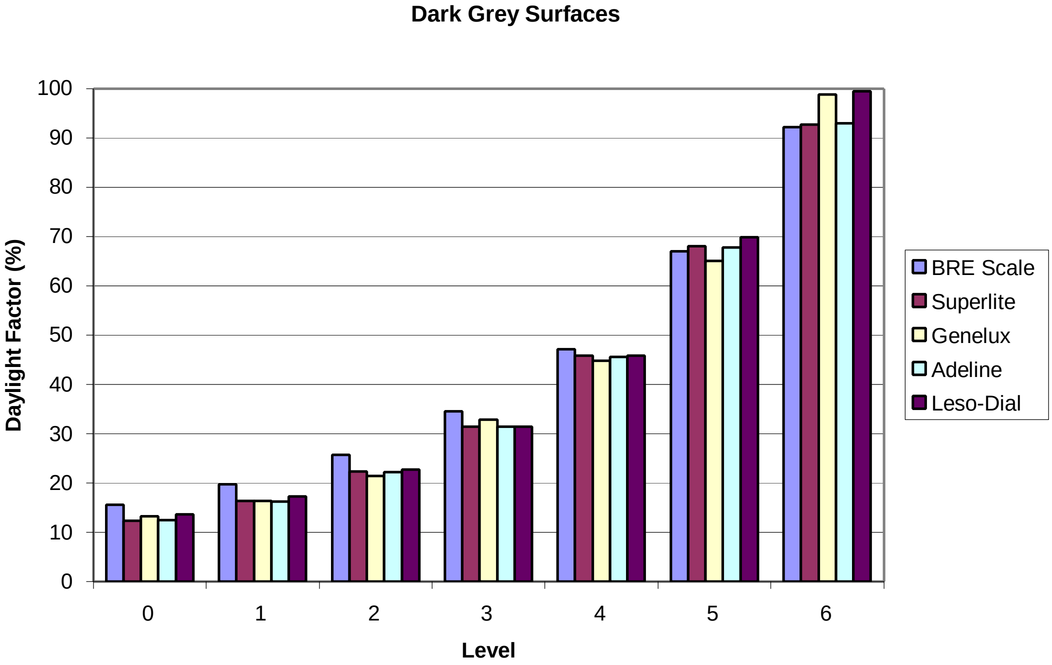

Figure 3: Comparison of results for BRE scale model tests on simple atrium for Dark Grey Surfaces

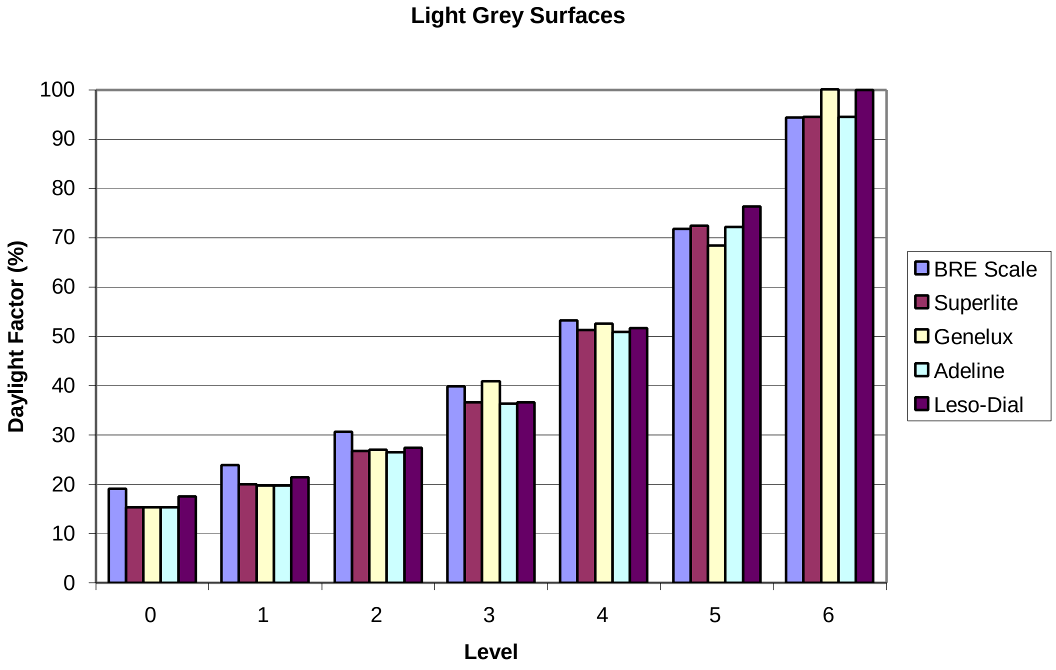

Figure 4: Comparison of results for BRE scale model tests on simple atrium for Light Grey Surfaces

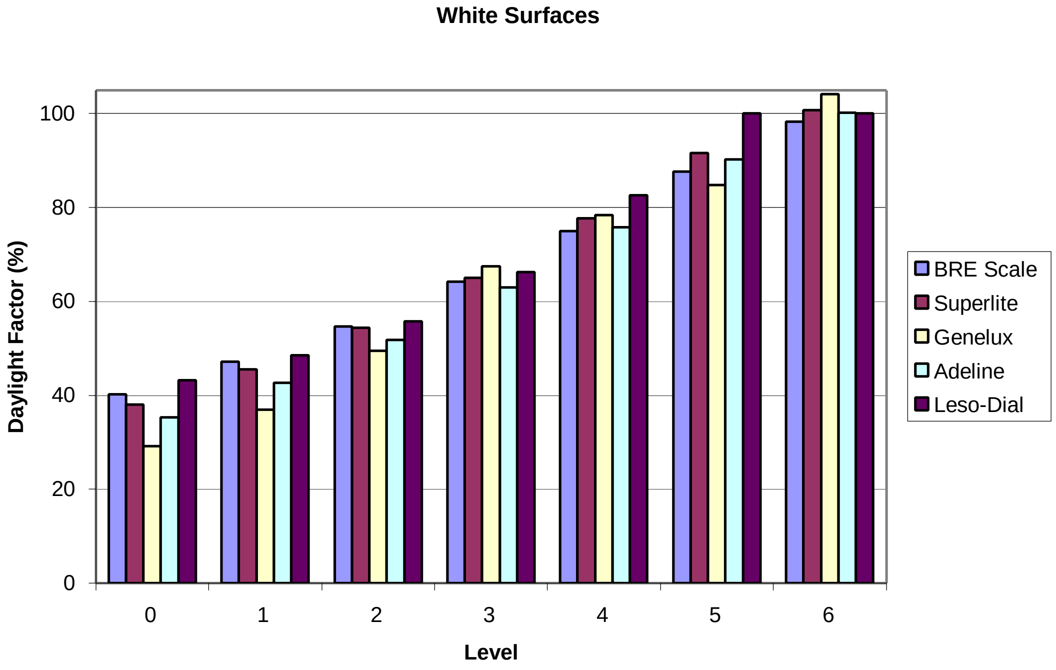

Figure 5: Comparison of results for BRE scale model tests on simple atrium for White Surfaces

5.3.2 BRE Scale Model tests on Complex Atrium

This model is an extension of the previous one, but somewhat more complex. A room is added to the atrium (at each level) and the illuminance computed within the room at varying distances from an opening in the atrium side wall. The atrium also has an optional saw-tooth roof light. The opening in the room is 6.25m long and 1.70m high located centrally and towards the top of the wall. See Fig 6.

For these tests all the sides of the atrium are either White (82%) or Black (4%) and the saw-tooth is White (82%) both inside and outside. For the room the following reflectances were used: Ceiling and walls: white (82%); floor: brown (13%); front of partition: grey (32%); back of partition: white (82%); back wall: black (4%).

All surfaces are again assumed to be perfect diffusers and the openings are without glazing. The partition is removable for different simulations. This series of tests involved various combinations of roof systems and the presence/absence of the internal partition. A selection of the results are presented in Figs 7 and 8.

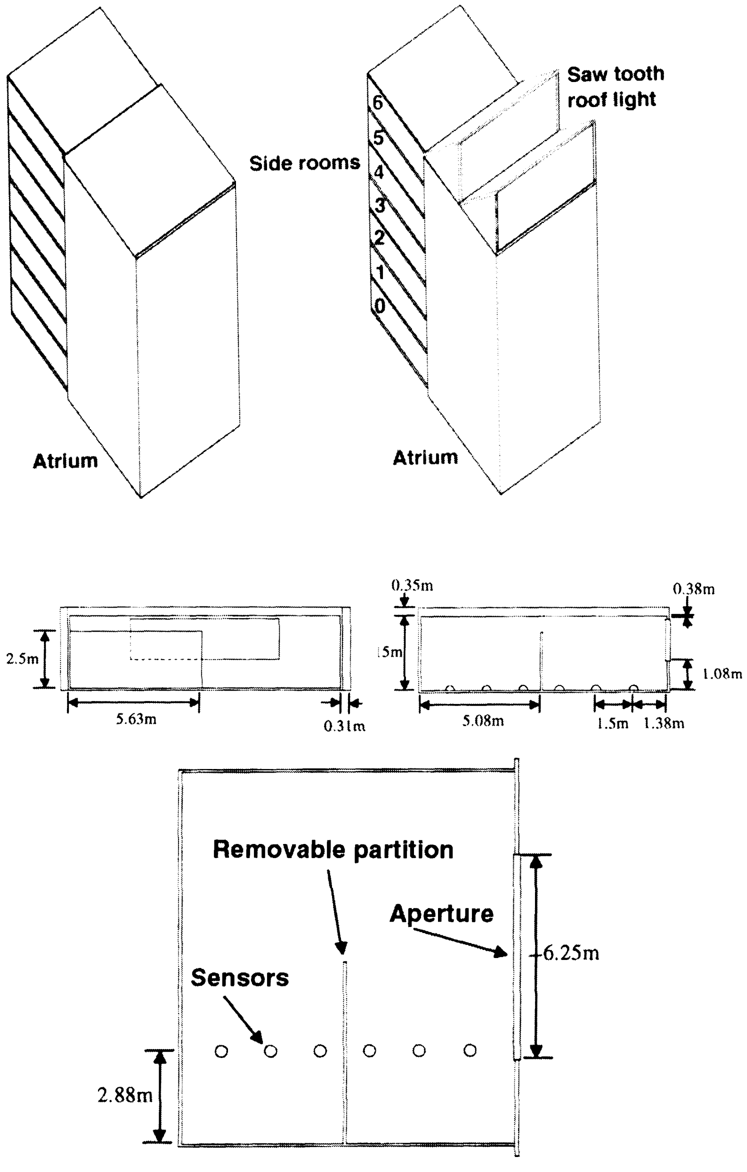

Figure 6: The BRE scale model with complex atrium

The recorded data from the BRE model is shown as the daylight factors at various distances from the window (atrium side) wall, together with simulation from the computer packages Genelux and RADIANCE. We present just two simulations for comparison. Fig 7 shows the results at level 6 and Figure 8 for level 4 (i.e. lower down the atrium).

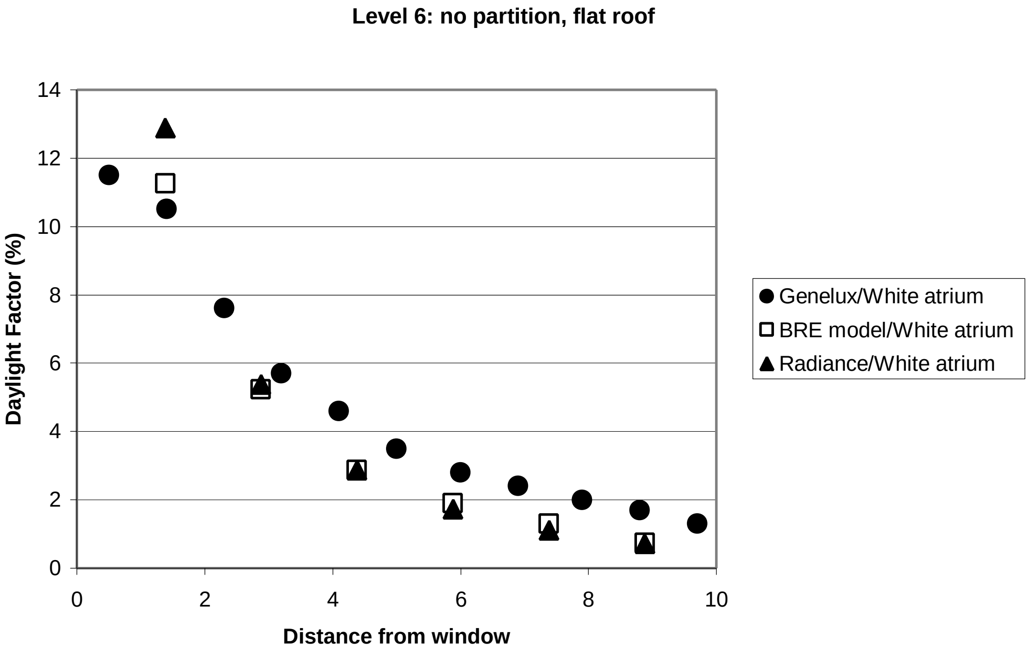

Figure 7: BRE Complex Atrium, at level 6

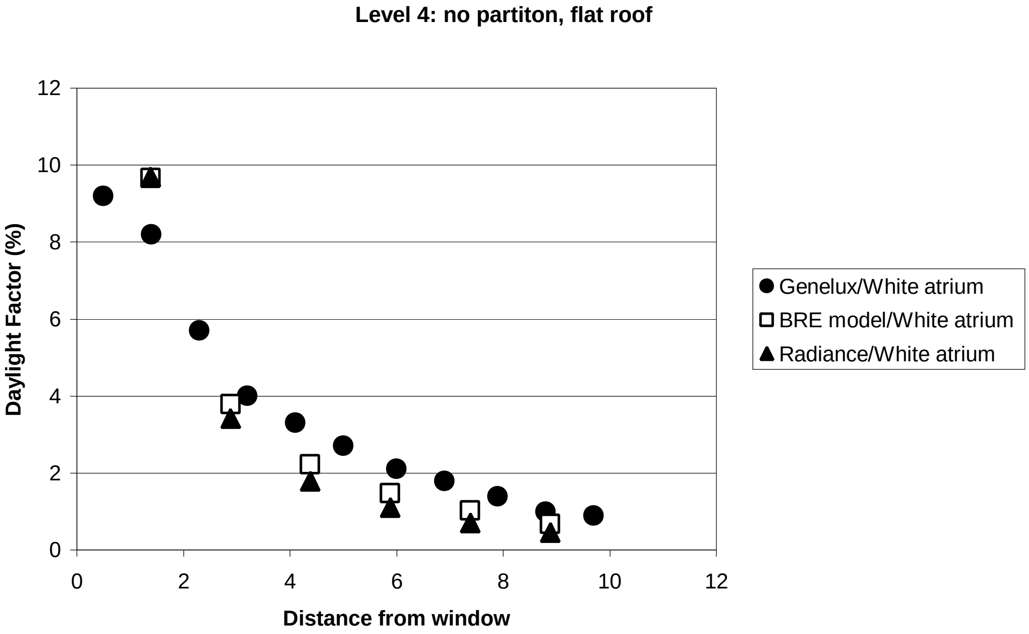

Figure 8: BRE Complex Atrium, at level 4

The notable results here are:

- RADIANCE provides a close approximation to results as measured on the BRE scale model. The differences are typically less than 10%
- Genelux, on the other hand provides estimates that are generally higher (>20%) except when close to the window.

The results shown on Figs 7 and 8 are typical of the other results obtained across the full set of measurements and simulations.

This model is naturally more complex that the previous one, hence requiring a better modelling strategy to give accurate results. Virtually all the light entering the room has been reflected (several times) down the atrium before entering the window.

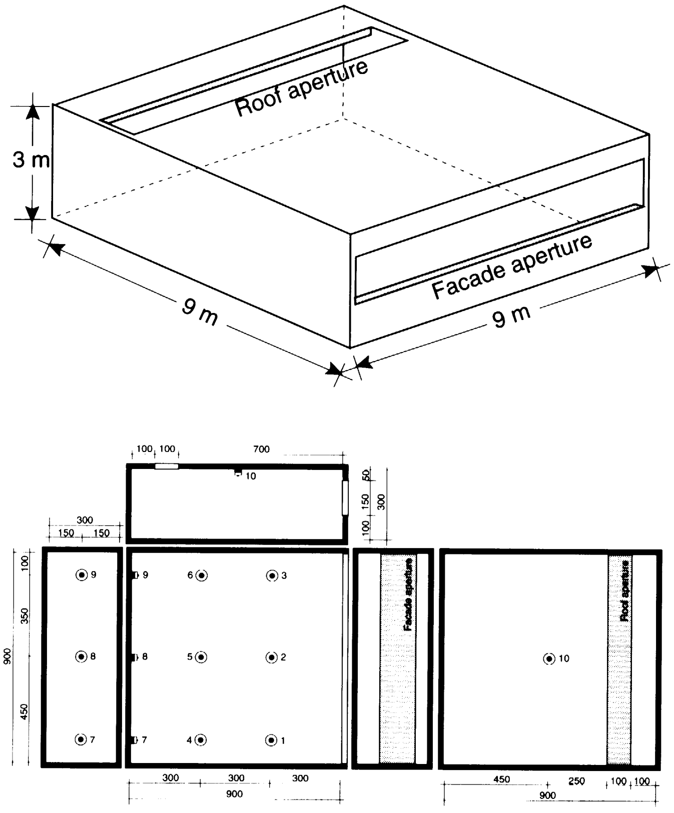

Figure 9: The CSTB Scale Model

5.3.3 ECAD/CSTB Scale Model

This model room adds the complexity of a roof light combined with a wall window as shown in Figure 9. The wall and roof apertures were directly exposed to a model (artificial) sky approximating the CIE overcast standard sky. It has 6 measurement locations on the floor of the room, plus 4 more on the walls and ceiling. This model was evaluated at Centre Scientifique et Technique du Bâtiment, France.

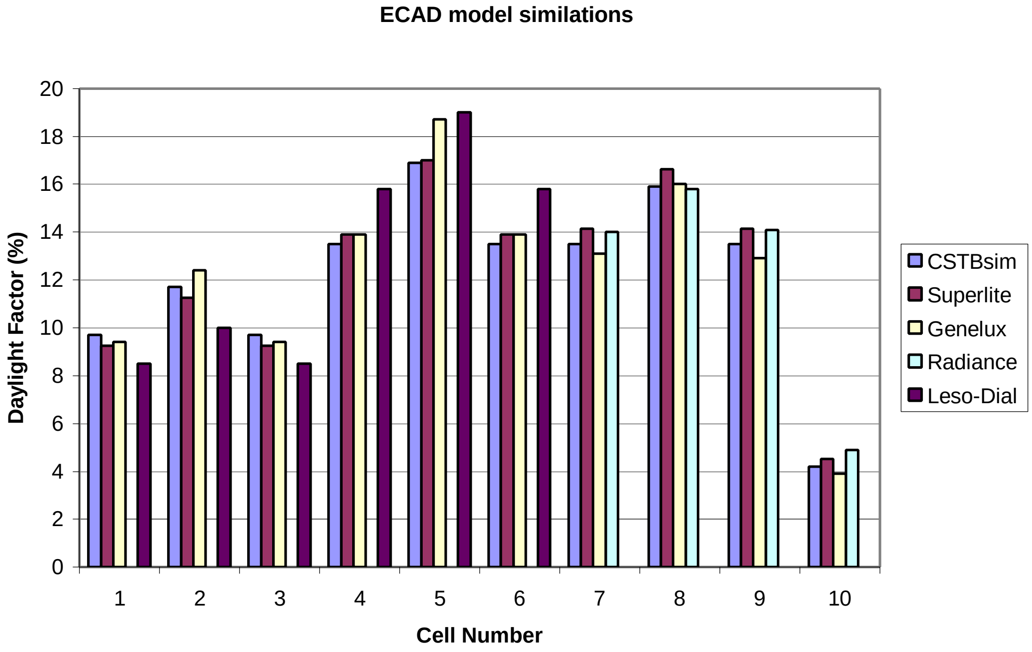

Figure 10: Comparison of several simulation packages on the CSTB model.

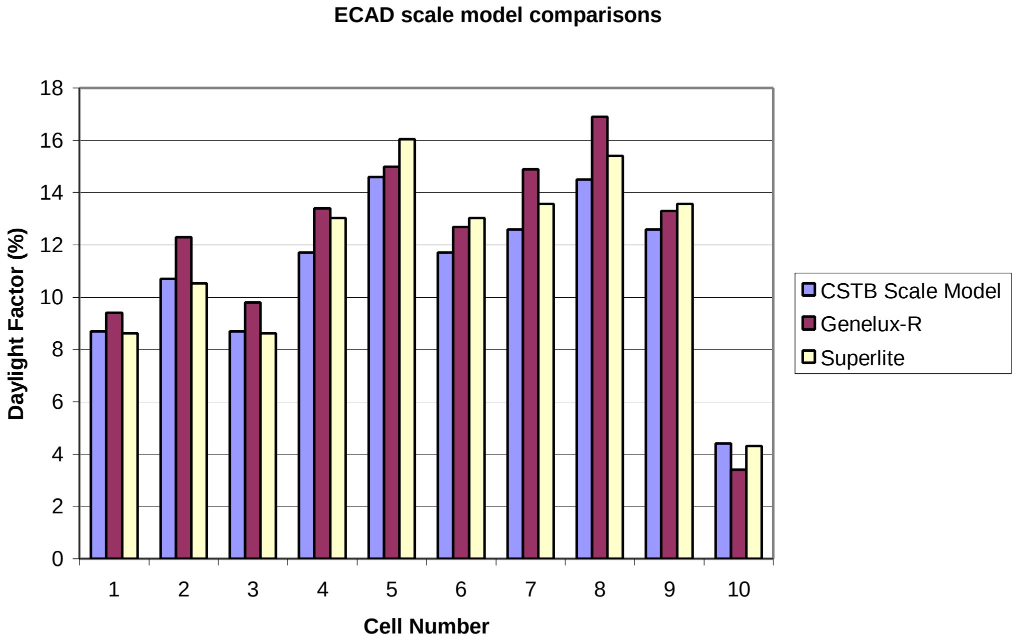

Figure 11: Comparisons with the CSTB scale model measurements

The surface reflectances are taken to be: floor 30%, walls 50% and ceiling 70%. Figure 10 shows a selection of the results from a series of simulations, thus comparing the simulation packages for the same assumed lighting conditions. We see again the differences between the various simulation packages are generally within a 5% range. Note that not all simulations were run on all sample points.

Figure 11 shows the results of the measurements taken from the scale model (inside an artificial sky) compared with two simulation packages.

5.3.4 LESO/EPFL Scale Model 1

This room model is a simple box-shaped room with a window opening at the end. In this case the scale model includes some window frame details that are not modelled in the computer programs. See Figure 12. The surface reflectances are: floor 28%, walls 60% and ceiling 83%. This modelling work was performed at Ecole Polytechnique Fédérale de Laussane, Switzerland.

Using a CIE overcast sky in the model sky, the measured values of the daylight factors for the cell positions A to G as shown in Figure 13. The results again show a close approximation even though the detail of the window frames has not been modelled. Note that in these results “Radiance” refers to the Unix version of RADIANCE and “Adeline” refers to the DOS version of RADIANCE which is packaged with Adeline.

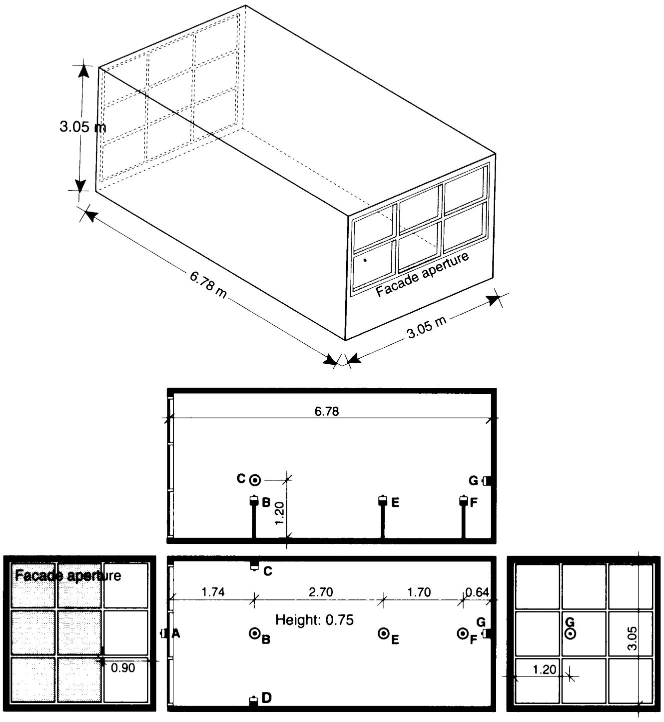

Figure 12: The LESO/EFPL model room

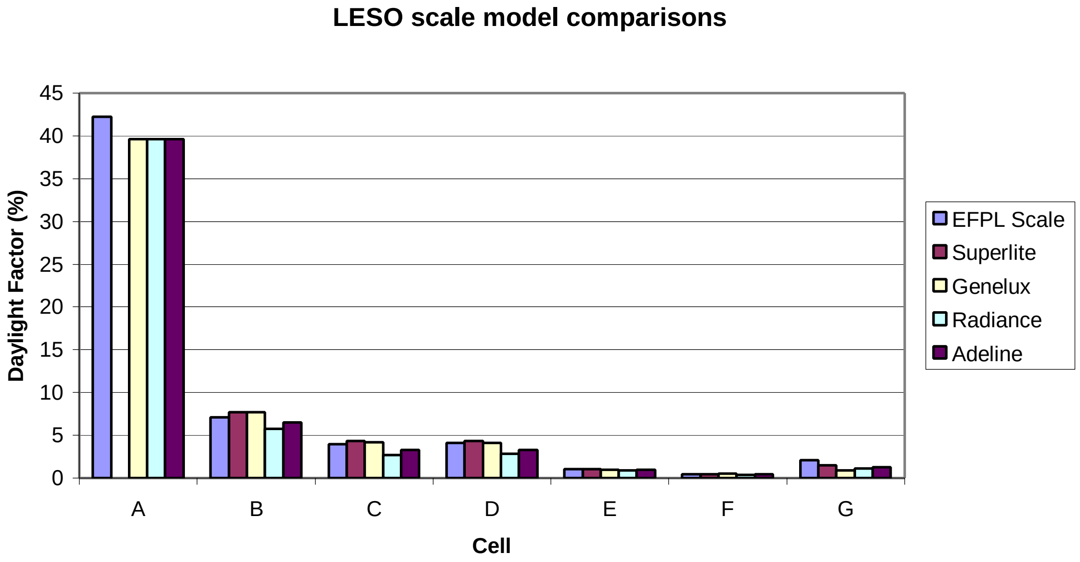

Figure 13: Comparing the LESO/EFPL scale model with simulation packages.

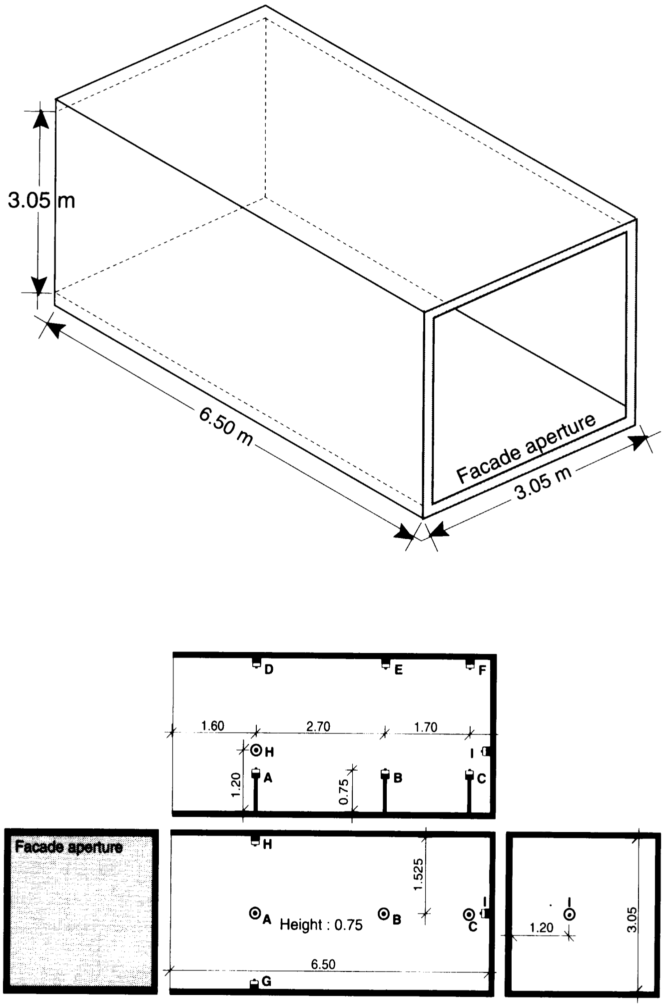

Figure 14: LESO/EFPL model 2

5.3.5 LESO/EPFL Scale Model 2

This model is basically the same as the previous one, except that the window has been simplified to occupy the full end of the room and some additional measurement points have been added. See Figure 14. The surface reflectances are: floor 28%, walls 60% and ceiling 83%. This modelling work was also performed at Ecole Polytechnique Fédérale de Laussane, Switzerland.

The simulation comparisons are shown in Figure 15. Again these are quite close to the measured values from the scale model.

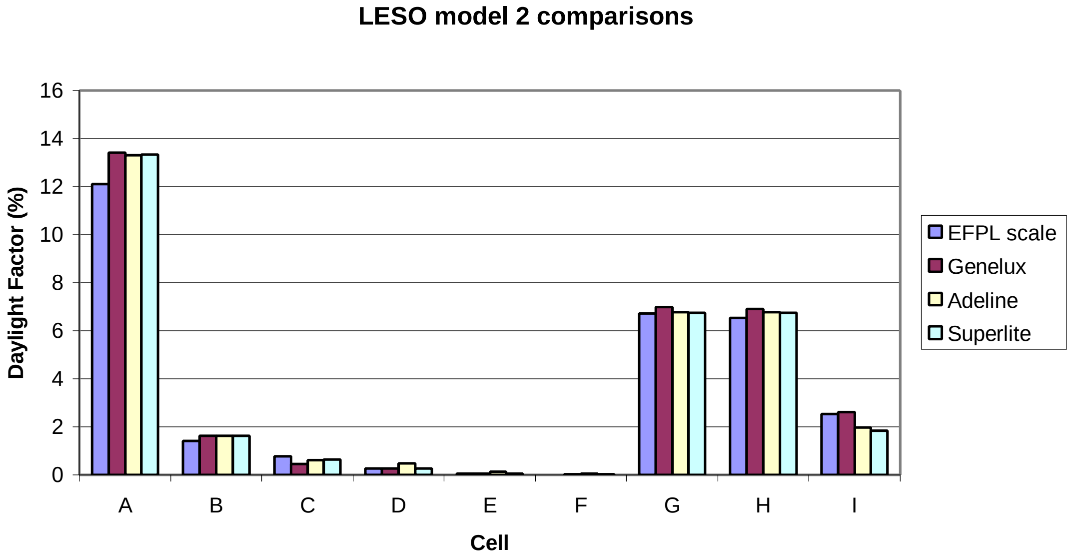

Figure 15: Comparison of the LESO/EFPL scale model 2 with simulation packages

5.3.6 A Comparison with Two Scale Models

This work was carried out by Joseph Ashmore and Paul Richens at the Martin Centre, Cambridge University (Ashmore and Richens [2001]). The test model comprised an empty room with two widows (0.9 x 1.34m with a 0.45m reveal) facing a courtyard with brick walls and grass ground cover. While the room is quite simple the external environment is not. See Fig 16. The courtyard is 5.125m x 5.275m with 3m high walls. There is an oversailing roof 0.85m deep and projecting 1.4m on the courtyard wall opposite the room.

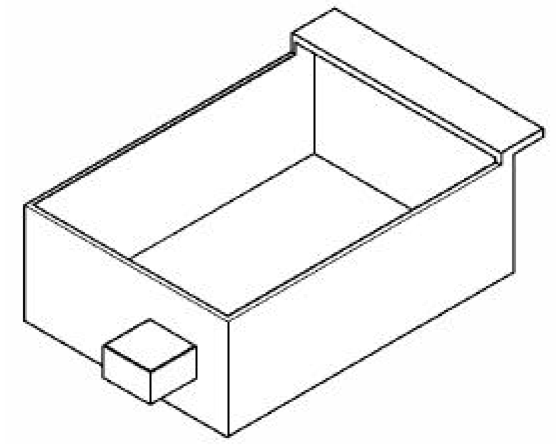

Figure 16: Courtyard models showing location of room

This model is quite complex, especially the external environment. The 1:50 scale model was measured in two different artificial skies (mirror sky, multisource sky), and simulated with four computer packages (Adeline, Lightscape, Microstation and RadioRay). A CIE overcast sky was simulated. In the scale models, measurements were made on a working plane height of 1.0m on a 0.5x0.5m grid. The computer packages were used to compute the values at the same locations. The results presented in Figure 17 show the averaged values (along each row of sampled points) for set distances from the window wall.

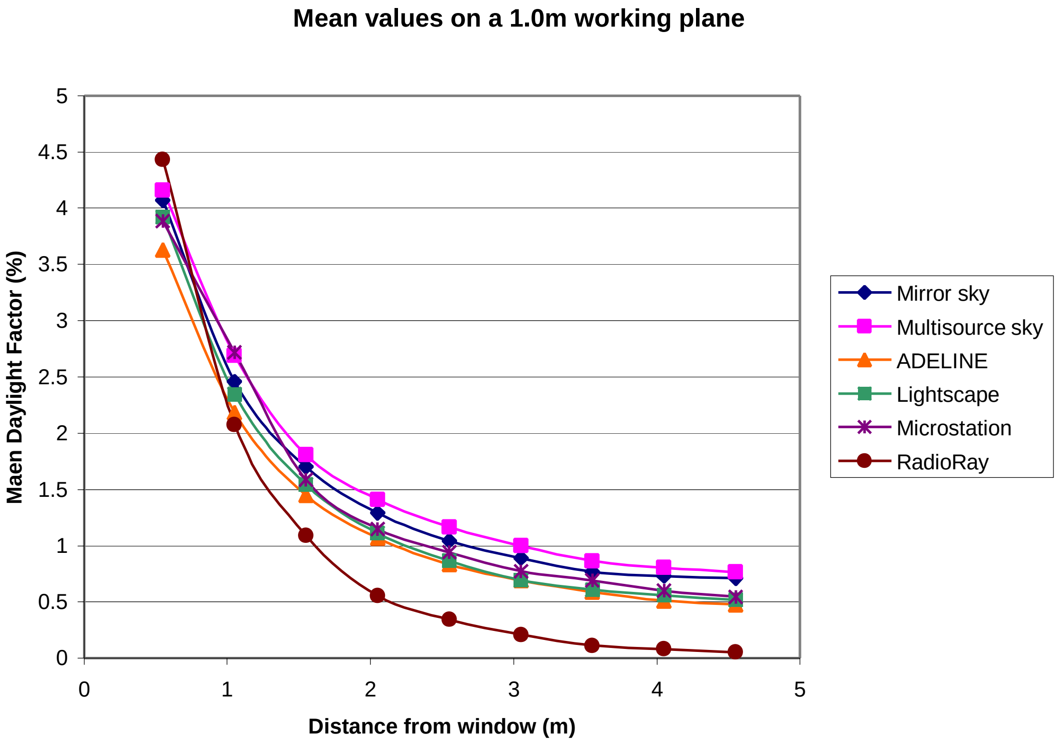

Figure 17: Comparison of scale model and simulated results

Firstly we see that the two artificial sky – scale model results are quite similar (Mirror sky at the Martin Centre and the Multisource sky located at University College London). Three of the four computer packages provided results close to the scale models (generally predicting lower values). The fourth (RadioRay) gave quite erroneous results. This package is no longer commercially available.

5.3.7 A Theoretical Analysis Comparison

All of the above results are based on a comparison with scale model measurements or comparison between simulation packages on the same scene. Khodulev and Kopylov, [1996] have attempted a comparison with a purely theoretical model. The model room is very simple, a cube (10m sides) with a point light source (50000cd) placed at its centre as shown in Figure 18. This work was carried at the Keldysh Institute of Applied Mathematics, Russian Academy of Sciences, and the Moscow State University.

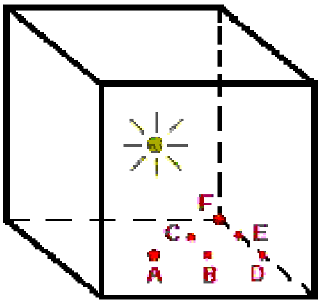

Figure 18: A simple cube-shaped room

The points labelled A to F were chosen to represent some key positions in the scene. The surfaces are white in colour and have a diffuse reflectance of 66%. We would expect more difficulty with simulating results near the edges and corners of the cube.

For this simple room it is possible to compute the theoretical surface luminances (with some care to handle singularities at the cube edges and corners). For this model three simulation packages were compared. The results are shown in Figure 19. Apart from Lightscape, the other two packages appear to give quite good results. Of course this is a very simple model and we might expect that the results should match very closely. Note that the results reported here are those that give the highest accuracy and thus may have consumed substantial computational times.

These results are amongst the very few where a theoretical model is compared.

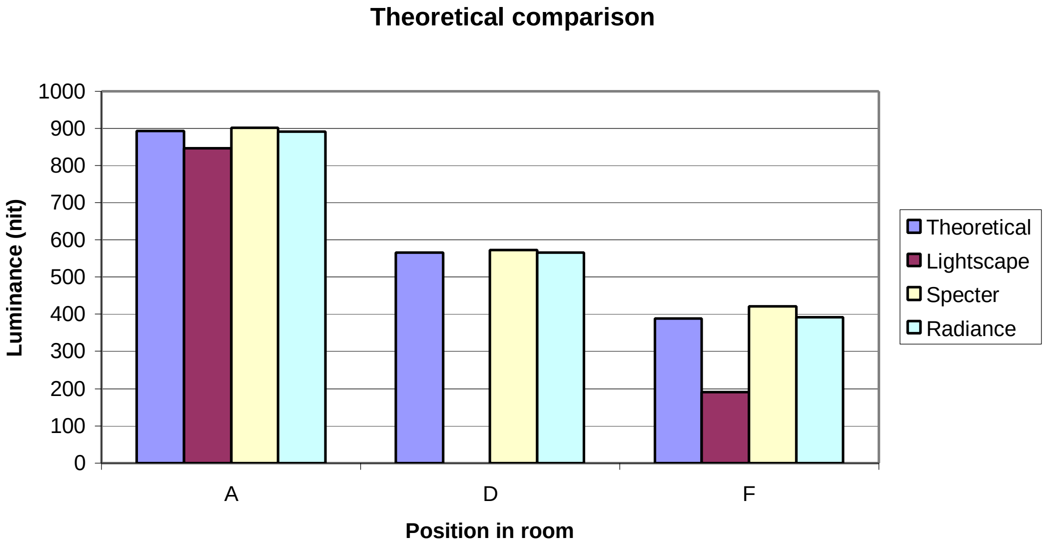

Figure 19: Comparison of theoretical model with simulation packages.

5.3.8 Simulating a Real Scene Inside a Room

Khodulev and Kopylov have also compared three simulation packages in a more complex (perhaps realistic) scene as shown in Fig 20. In this scene three points were chosen for comparison: point A is in the middle of the table top, point B is on the floor between the nearest two chairs, and point C is in the far left corner of the room. The resulting luminances are shown in Figure 21.

Figure 20: A model scene (Radiance output)

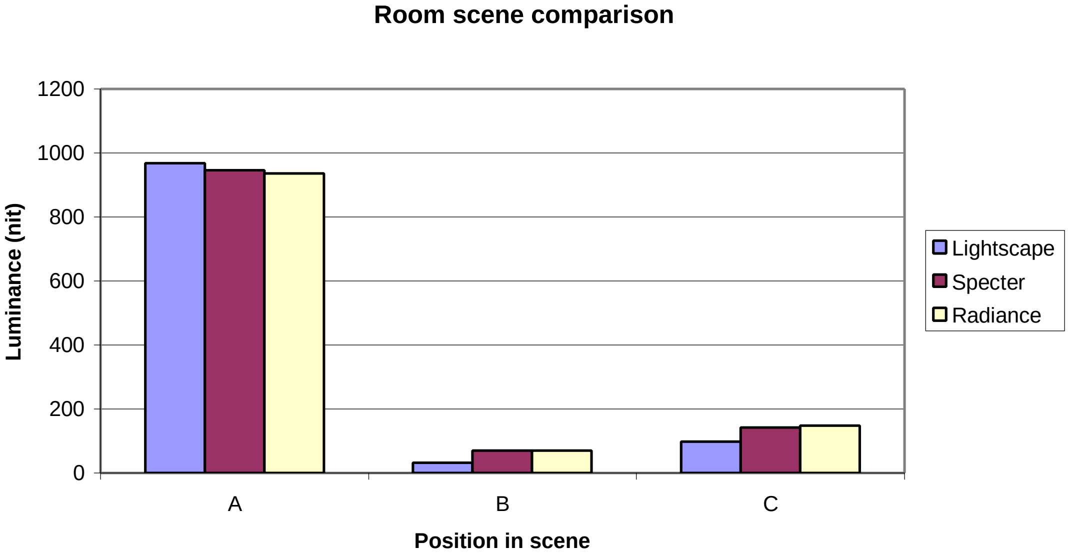

Figure 21: Comparing simulation packages in a room scene

5.3.9 Comparing Complex Scene with Measured Luminances

Ashdown [1995] has reported the results of an attempt to compare simulation results with actual measurements taken in a real scene using a CCD camera and a calibrated digital image. The idea here was to extract luminance values from a CCD image of a scene and compare these with the simulated values. The idea sounds good, and if it could be made to work it may provide a way of validating simulation packages in more complex (perhaps realistic) scenes.

Ashdown reported major problems in this approach, in particular aligning the CCD image to the model data (locations). The computational tasks involve identifying objects in the CCD image that can be related to the actual scene (e.g. edges of objects, wall corners, door openings, furniture, picture frames and so on) and then “mapping” the image onto the geometry of the scene so that points of interest can be aligned.

No useful results have yet been reported from this work.

6 Skies as Light Sources

For design situations where daylight will play a significant role in the lighting of a building’s interior the choice of appropriate sky conditions is essential. Daylight naturally varies dynamically due to both the movement of the sun, but also due to effects of cloud and other atmospheric effects (pollution, humidity, and so on). Most simulation packages allow the user to select one of the standard CIE sky luminance models (clear, overcast, intermediate).

The CIE sky models cannot be described as representing all sky conditions in a reliable way – these vary too much to be captured in 2 or 3 model formulations. Recently Kittler, Darula and Perez [1997, 1998] have proposed a much more comprehensive set of models (the SSLD[6] models) which are aimed at being able to represent a much wider set of actual conditions. These models are naturally parameterized to suit local conditions, so the user is required to have an appreciation of these parameters and how to choose them. These new sky models are still under consideration for adoption as a standard by CIE, though recent publications by Tregenza [2000] and Roy el al [2000] have demonstrated some aspects of their validity in a range of climate conditions.

While these new models are quite complex to use directly, in time we could expect them to be embedded into simulation packages. In the mean time it is possible for interested users to access this new family of models and compare them with the older CIE models for their own location. There is an on-line site provided by Roy [2000] that is publicly accessible[7]. The “SDF-web client” model allows a visitor to the web site to build SSLD models to suit their local conditions, view and compare these with other standard models, and download the models in SDF[8] format for use in their simulation models. Currently these SDF models require access to a library of C-language program functions that must be formally included into the simulation package.

7 Summary

The work presented in this report represents a collection of already published data on a selection of simulation packages. While there have been some attempts to undertake well controlled comparative studies (e.g. Fontoynont, 1999), there is in general only ad hoc results reported from researchers working with the tools they had available at the time. Even for the results reported by Fontoynont various simulation packages have been used in different building contexts.

To some extent this is not surprising. There is not a great deal of incentive for package providers/developers to put their product on the line (so to speak). It would also be a relatively costly process to complete a thorough and systematic comparison of all (probably most) the commercially available packages. Such a task is yet to be attempted.

For the potential user of these simulation packages, some clear indications of accuracy, and in what conditions, is of value. But, basically, we can conclude there is no definitive answer to the question: Which is best? We can reach some useful conclusions however.

Firstly, we must reinforce the fact that this study has not included all available packages and thus recognises that there may well be other as good (or better)

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[6] Standard Sky Luminance Distribution

[7] By request a user can ask for their own user ID.

[8] Standard Digital Form

simulation packages available. We have not been able to locate results from suitable tests that could be included in this report.

Most of the packages examined in this report appear to give useful results. There are reasonable comparisons with measured (scale model) values, and often quite similar results for equivalent simulation tasks. There are indications that as the simulation tasks get more difficult; the differences (errors!) start to become more noticeable. The primary source of errors most probably arise from the way that surface reflections are handled, and any errors are multiplied as more reflections are necessary to account for light entering deep into building spaces.

It should also be noted that all the case studies presented are still relatively simple when compared to the real world. Surfaces are generally assumed perfect diffusers and the presence of interior fittings and furniture most often neglected. This may well lead us to retain a degree of scepticism about the reliability of the results.

We also should not under estimate the amount of work required to build the required model definitions to enable effective lighting simulations to be performed. There is often considerable work required to build the geometric models (from scratch, by hand) or even to convert from 3D CAD models that might be available from other design packages. It is true now, and will probably remain so, that there are necessary simplifications in the geometry to enable suitable models to be built for lighting simulations. The computation times can still be quite significant (can be several hours) and this mitigates against a lot of experimentation with scene geometry and optical properties.

Perhaps the clear outcome from the results presented in this report is that the RADIANCE package appears to be well positioned amongst all of the others, and seems to be able to produce a consistent level of accuracy when compared to theoretical, scale model and a selection of other simulation packages. The underlying theoretical models and their implementation appears to be the most well developed for photometric accuracy.

In its basic form (Unix version) there is no really good front end to assist users in developing and testing their models, or to automatically build models from CAD design packages. The Adeline package goes someway to this end, but the 3D (Scribe) modeller is poor at best.

There are some indications that this problem is about to be redressed. There are now several plug-in packages for Autocad (AutoDesk Inc) which provide the connection between the CAD drawing and the data requirements of RADIANCE. Of these Desktop Radiance and Rayfront seem offer some potential. A user must already hold a license for Autocad to use these plug-ins.

The integrity of these interfaces/converters (as claimed by the developers) has not been evaluated, but they do show some promise in providing a way of simplifying the preparation of data for the model. There are in fact a number of tools that operate this way, using Autocad as a starting point. These can be found at the Radiance[9] and Autodesk[10] web sites.

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[9] http://radsite.lbl.gov

[10] http://www.autodesk.com

8 References

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9 Appendix

9.1 List of Software Packages Cited

The following packages have been cited in this report. This list is not intended to be exhaustive of lighting simulation packages, there are many more of these. Those listed below have been referenced in one or more of the reported studies that comment on, or compare, packages for their accuracy and/or usability. Note that the behaviour and performance of any package may vary with version being used.

Name of Package	**Operating System**	**Information Source/Comments**
Adeline	MS Windows	http://www.IBP.FhG.de/wt/adeline Fraunhofer-Institut fur Bauphisik, Stuttgart, Germany http://radsite.lbl.gov/adeline/HOME.html Lawrenece Berkeley National Laboratory, Berkeley, Califorinia, USA Uses a PC version of Radiance
Microstation	MS Windows	http://www.bentley.com Bentley Systems Inc, Exton, Pennsylvania, USA
RadioRay (plugin for 3DStudioMax)	MS Windows	http://ktx.com/plug-ins Kinetix, a division of Autodesk Inc, San Francisco, USA (possibly no longer available)
Lightscape	MS Windows Unix	http://www.lightscape.com Autodesk Inc, San Jose, California, USA
Specter		http://www.integra.co.jp/eng/products/specter/index.htm Integra Inc, Japan
Radiance	Unix	http://radsite.lbl.gov/radiance/HOME.html Lawrence Berkeley National Laboratory, Berkeley, California, USA. This is the most commonly used simulation package and is integrated into a number of others (eg Adeline). It is also freely available (Unix only).
Genelux	Web-based and Unix	http://genelux.entpe.fr/ Light and Radiation Group,Département Génie Civil et Bâtiment, URA CNRS Ecole Nationale des Travaux Publics de l'Etat Vaulx-en-Velin, Lyon Cédex, France This is a fully fledged simulation package, a version of which can be accessed via the web where the user uploads a data file, the simulation is done at the server, and the results downloaded to the user.
Leso-Dial	MS Windows	http://lesowww.epfl.ch/anglais/Leso_a_software_lesodial-e.html Laboratoire d'énergie solaire et de physique du bâtiment EPFL - LESO-PB / ITB, CH - 1015 LAUSANNE This package offers the user pre-packaged example

		designs via a lexicon of examples from which some typical lighting data can be looked up. It is not a simulation package.
CSTBsim		CSTB “Naturel” software Centre Scientifique et Technique du Bâtiment, France
Rayfront (converter for Autocad)	MS Windows	Schorsch Inc. http://www.schorsch.com A converter for Autocad files to RADIANCE input.
Radout (converter for Autocad)	MS Windows	Space & Light, 2164 Jefferson Ave, Berkeley, CA, USA. http://www.dnia.com/~chas/radiance/radout.html A converter for Autocad files to RADIANCE input.
Desktop Radiance	MS Windows	http://radsite.lbl.gov/radiance/HOME.html Lawrence Berkeley National Laboratory, Berkeley, California, USA. This a new plug-in for AutoCad to prepare data files for RADIANCE
RADTOOL	MS Windows	School of Architecture, The University of Western Australa http://fridge.arch.uwa.edu.au This tool assists in the preparation of input files for RADIANCE

9.2 The Ideal Rendering Package

This section has been provided by Joseph Ashmore and Paul Richens from their work at the Martin Centre, University of Cambridge. Some additional notes have been added by the author (*shown in italics*). It provides a commentary for the data reproduced in Table 3. In some ways this review provides a check-list for selecting, or assessing, a lighting simulation package, and as such provides a useful reference for this purpose.

Overview

In an ideal world, an unskilled user would be able to take the model from any CAD system, quickly and easily set up the materials of the surfaces, hit a render button and a photometrically correct, photorealistic image would be displayed, giving easy access to all of the photometric data. Current rendering systems are not yet capable of this level of simplicity of interface, so instead we will comment upon the major sticking points of the current rendering systems

Photometrically correct

The final result needs to be photometrically correct, for the given input values. *It is essential that the user can rely on the integrity of the computations, and know what limits are present, explicit or implicit in the modelling methodology.*

Materials

Material properties affect all the characteristics of the light as it is reflected and refracted through the scene.

Non-uniform BRDFs

Although some applications may need the ability to model directionally dependent reflectance functions, in general this is more advanced than the requirements of most users. Indeed the additional complexities introduced may hamper some users. Perhaps one of the biggest problems with non-uniform BRDFs is the difficulty in getting the data for materials from suppliers. This limits their necessity in a modelling system

Refractive and partially transparent materials.

The ability to model partially transparent materials such as glass is obviously very important in the daylighting context. Ideally lighting simulation software should be able to model these materials.

Specular to diffuse reflections

Modelling specular to diffuse reflections has many applications in daylighting. Mirrored light shelves and blinds are standard examples of where such functionality would be of use.

Model dimensions

The model needs to accurately mimic the dimensions of the real room. For any double precision CAD system this should not prove to be a problem.

Variety of Sky models

A wide variety of sky conditions should be supported. The standard CIE or IES clear and overcast skies should be included. A database of sky data for specific locations could be useful for some applications. The unobstructed sky illuminance should default to a sensible value for the given time and location. *As new sky models (that can better represent local conditions) become available these should be able to be accessed from simulation packages.*

Chromatically correct

The renderings need to be chromatically correct. There is some concern that in some modelling systems, diffuse reflection from a coloured source causes light emission of only that colour.

Scale invariance

The scale of the model should not affect the daylighting solution.

Quality of visual output

The quality of the visual output is clearly important for photorealistic images.

Common rendering errors

Rendering errors result from various computational artefacts. Some of these will come from inaccuracies in model specification (surface not aligned exactly), but some can be caused by computational errors due to number round-off.

Mottled due to sky under-sampling

This occurs noticeably in the radiosity renderers, and in physical models where the artificial sky has discontinuities between its light sources. There is room for research into reducing this effect in radiosity renderers

Shadow leaks

Shadow leaks occur frequently in Radiosity renderers. They occur where a plane intersects a patch in the radiosity mesh. If the illumination levels on either side of the patch are very different, then the under lit nature of one side will bleed into the lighter side. This is because in the final display of a radiosity solution, the illuminance of each patch is calculated by interpolating between sampling points on the patch. The effect of shadow leaks is particularly strong when the meshing is coarse. Increasing the fineness of the mesh may reduce shadow leaks but will increase rendering times.

Light leaks

Light leaks can be a very serious problem in the rendering process. A slight geometrical error in its construction can cause light to leak into a model. Light leaks can occur in two ways, either through geometry not matching, leaving holes for light to pour in, or through a process similar to that which causes shadow leaks. A particularly severe case occurred in Microstation where unless a relatively obscure option was selected, all geometry outside the field of view was omitted causing the room to be flooded with light.

Blocky shadows

These occur where the meshing of a surface along a shadow boundary is so coarse that the observer can resolve steps due to the mesh size.

Missing features (poor shadows)

This occurs in radiosity renderers where an object such as a table does not meet the shadow that it has created.

Mach bands

These occur where incremental changes in linear intensity across a polygon boundary confuse the human visual system into perceiving a band. They occur where the shading between meshes has not been continuous.

Interface

The user interface concerns the ease with which the user (both beginner and experienced) can construct and edit the geometric model of the scene and the optical properties of the objects in the scene.

Model geometry

The construction of the model geometry is a central problem, and there is considerable interest in being able to use models generated for other purposes, especially CAD models for working drawings and physical design.

Ease of import of models

Models should be straightforward to import. *Ideally it should be possible to define both the geometry and the material properties within a CAD package*

Portability of models

Models should be easy to move about between computers. Microstation (Vers 7.1) suffers from needing up to five separate files for a model (geometry, two material, rendering settings, radiosity file). Models in ADELINE (Vers 2.0NT) have path dependence, and will not allow models to be held on different drives. This makes it difficult to transport models from site to site.

Takes any model from any CAD system

Ideally models could be created in any CAD system and used in the renderer.

Light leaks and shadow leaks easy to fix.

Ideally neither light leaks nor shadow leaks should occur. If they do occur, there should be simple tools to

Add patches to cover up holes

Move vertices to lie coincident with other vertices

Transform and translate planes.

Accuracy of model

Care need be taken with the numeric precision of the model. Repeated translations should not alter geometry through rounding errors.

Display of meshing.

If the renderer needs to mesh the scene, it is useful to display the mesh used, to give the user an idea of what is happening.

User control over meshing

It is useful to give the user some control over the meshing of individual surfaces, and the ability to ignore other surfaces

Materials

Material properties are often difficult to obtain, hence it is usual to expect these to be provided in a library that is directly accessible in the model building phase.

Simple to understand and set up

Materials should be simple to understand and set up.

Materials Library

Inclusion of a basic materials library would be useful to many users, avoiding the need to know the reflectances of various materials.

Cameras

Cameras and viewpoints should be easy to set up. They should also be easy to save and to return to. Once set up they should not change unless explicitly requested by the user (Microstation (Vers 7.0) suffers in this respect).

Sky models

An interface for setting the sky parameters needs to allow the user to simply define

i) North,

ii) The altitude and Azimuth of the sun, based either on time and geographic location or as direct data entry.

iii) Intensity control giving the unobstructed sky illuminance – rather than a variable.

iv) Solar colour.

Lights

Additional lights should be easy to add and simple to scale in relation to the sky intensity, luminance required. This would be particularly useful if a control value, such as a computer monitor with an illuminance of 70 Lux was required in the scene.

Empirical controls

Sliding controls on sensible scales are a useful way of intuitively setting various parameters. A good example is in ADELINE where there is a control for the required image quality. This is simply set at low, medium or high.

Stability

The system should be relatively bug free and neither crash nor hang unexpectedly.

Help/support

Online support

Should be simple to use, well indexed and full of information containing all that is needed to understand the rendering application

Email / telephone support

Should be swift and comprehensive.

Threading

As rendering processes are computationally intensive, the rendering applications should be well threaded to allow the user to carry on other tasks whilst the rendering is in progress.

Speed

The rendering should be fast allowing the user to quickly complete his job and to prevent errors as soon as they appear. Ideally it would be possible to create real time walkthroughs of the model, without pre-rendering. Progressive type algorithms with continual display are preferable as they allow the user to get initial results quickly.

Progress bars

The progress bar should be accurate and proceed at a constant rate. It should not disappear for long periods of time. It should be based on time remaining rather than on percentage of energy remaining

Ease of setting up renderings

Rendering settings should be easy to set up and there should be the minimum of controls. Those controls that are there should be easily understandable.

Display mapping

Of the mapping techniques available, ADELINE proved simplest, automatically calculating exposures, using a linear scale factor. The interactive brightness/contrast sliders of Lightscape also proved simple to use.

Memory

Ideally any simulation program would be economical with memory and never run out of it. This is becoming less critical with decreasing memory prices, but was still found to be an issue with some renderers.

Sealed environment

Some simulators need a sealed environment to work in, whilst others need none.

Output available

The results of the simulation should be available in a number of forms to allow them to be saved for later re-display, as well as for importing into other image display packages and/or spreadsheet packages where access to numerical values are required.

Photorealistic data

Photorealistic data generally comes as an image bitmap that has been constructed to suit the resolution of the screen, or saved to a file at higher resolution. High resolution images are important for quality presentations.

Bitmap images

All rendering systems should be able to create bitmap images. Ideally other image file formats (i.e. tiff) should be supported

VRML

Virtual reality mark-up language files should be created allowing a quick walk-through of a rendered solution

QTVR

QuickTime Virtual Reality should be easy to create to give another means to navigate within a rendered world

Animations of pre-programmed changeable lights

Tools should exist to create a film of the changing lights. A major application of this is with the moving of the sun. This should include attenuation of the solar intensity with solar altitude and changing solar colour with altitude. There should also be a constant meshing algorithm. It would also be nice if this could be combined with either walkthrough animation or QTVR to give a walkthrough animation with a slider to change the time of day or to control a lighting dimmer switch.

Walkthrough animations

Walkthrough animations should be easy to set up and render. Interlacing and antialiasing of images are important tools for producing animations.

Photometric data

Photometric data is essentially numeric, but to be useful it should be available as numeric values, say on a predefined grid of points, or concerted into iso-luminance contour maps on the surfaces in the scene.

Illuminance / luminance contour plots

The ability to create plots of a working plane with marked contours of constant illuminance.

Pick illuminance / luminance

The ability to measure the illuminance / luminance at a point selected by a mouse click – (it would be nice to be able to do this by keyboard co-ordinate entry as well). Maximum, minimum and average illuminances for that patch are also given in some packages, although maximum and minimum illuminances for the working plane may be more useful.

Use of working plane

Not all software is capable of creating a working plane on which illuminances can be recorded. Other software such as ADELINE creates a working plane but fails[11] to give a way of taking measurements from precise locations.

Display of values across a grid

Lightscape allows the user to create a grid of readings across any plane with a single mouse click. This is a nice way of allowing systematic, quick access to illuminance data across an entire working plane

Automatic calculation of DFs

The option to display DFs, rather than raw illuminances / luminances would be useful.

Calculation of max/min DF and fraction above given %

Tools to display maximum and minimum DFs and the fraction of DFs on a working plane above a given threshold would be of use to daylight designers.

User access to illuminance data through customisable user interface.

It would be nice for the user to have access to the illuminance data through a customisable user interface. This would allow the user to select which data they wanted and to display it as they wanted

Image display

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[11] It is in fact possible to do this with Adeline, but not easily, and requires direct access to user generated input files.

The display of images on a screen, or printed on paper/film, requires a range of value judgements to set appropriate brightness levels and the dynamic ranges which can be represented on the particular display device.

Mapping techniques

Of the mapping techniques available, ADELINE proved simplest, automatically calculating exposures, using a linear scale factor. The interactive brightness/contrast sliders of Lightscape also proved simple to use.

Standalone v. integrated renderers

Creating an entire new CAD system to run with a radiosity renderer is expensive in programming time and is difficult for new users to learn. It is better to write the renderer as a plugin to an existing piece of software (which limits the user base), or to write the renderer as a standalone piece of software that takes input from a variety of other sources. It can either do this by directly importing the files or by having a file exportation plugin that runs from within other CAD systems.

Standalone renderers have the distinct advantage that they can take inputs from a variety of different modelling systems which the user may be familiar with.

Network Rendering

The use of parallel processing (distributing the rendering computational task to several and/or more powerful computers) is very important for rendering animations and walkthroughs. Lightscape does this well, and the Unix implementation of RADIANCE provides some tools to this also.