Comparative Evaluation of Four Daylighting Software Programs

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ABSTRACT

By the mid-1980's, a number of software packages were under development to predict daylighting performance in buildings, in particular illumination levels in daylighted spaces. An evaluation in 1988 by Ubbelohde et al. demonstrated that none of the software then available was capable of predicting the simplest of real daylighting designs. In the last ten years computer capabilities have evolved rapidly and we have four major packages widely available in the United States. This paper presents a comparative evaluation from the perspective of building and daylighting design practice. A contemporary building completed in 1993 was used as a base case for evaluation. We present the results from field measurements, software predictions and physical modeling as a basis for discussing the capabilities of the software packages in architectural design practice. We found the current software packages far more powerful and nuanced in their ability to predict daylight than previously. Some can accurately predict quantitative daylight performance under varying sky conditions and produce handsome and accurate visualizations of the space. The programs differ significantly, however, in their ease of use, modeling basis and the emphasis between quantitative predictions and visualization in the output.

Introduction

As the practice of architecture and lighting design have become increasingly computerized, the potential application of daylighting prediction software has also grown. Traditional tools used to predict daylight performance range from simple rules of thumb to calculation methods such as the lumen method, graphic methods such as the Waldram diagrams and the BRE protractors and to the use of physical models under a natural or artificial sky (Baker et al. 1993, F.1-13; Bryan 1986; Hopkinson et al. 1963; Robbins 1986, 157-235). With each of these, the designer hopes to predict at least the interior illumination levels in the building. With known daylight illumination levels under varying sky conditions, one can estimate the potential energy impact of daylighting and design the electrical lighting system in complement with daylight.

With a good physical model, the visual effect of the daylight design can be simulated in addition to producing accurate quantitative predictions of illumination levels in a space. In calculation techniques, the accuracy of prediction tends to increase with the increased complexity of calculations, assuming the underlying physical algorithms are correct. It is also more likely that the calculation can reveal daylighting nuances, such as distribution patterns, intensity and luminance gradations and potential glare conditions. It has therefore been assumed by many in the design profession that the computer will bring the highest possible level of accuracy to the prediction of daylight in buildings and render all other techniques obsolete.

Computer software for simulating daylighting performance, however, has faced serious obstacles, most importantly the speed and memory of desktop machines. A study of daylighting software available to designers in 1988 (Ubbelohde et al. 1989) demonstrated that the task of defining the architectural characteristics of a room and glazing system and then coupling those with the characteristics of a natural sky distribution taxed even most advanced desktop machines available.

This study focuses on four software packages readily available to architects and lighting designers in North America a decade later: Lumen Micro from Lighting Technologies Inc. (*www.lighting-technologies.com*); SuperLite and Radiance from the Environmental Energy Technology Division, Building Technologies Program at Lawrence Berkeley National Laboratory (*eetd.lbl.gov* and *radsite.lbl.gov/radiance/HOME.html*); and Lightscape Visualization System from Lightscape Technologies, Inc. (*www.lightscape.com*). All four software packages run on PC's likely to be found in an architect's or consultant's office.

There are additional software packages in existence which we did not examine. Some large architecture and engineering firms with offices in the United States and abroad (such as Hellmuth, Obata + Kassabaum, Skidmore Owings & Merrill LLP and Ove Arup) have developed proprietary daylighting software which is not available to outside designers. Daylighting software packages used abroad, such as Specter in Japan (Khodulev & Kopylov 1996) and Genelux (Baker 1993, G.4) and Optis Light (IESNA 1997) in France, require graphic work stations or mainframe computers and are not widely available in the United States. Software packages released recently, such as RadioRay plug-in for 3D Studio MAX and 3D Studio VIZ (*www.ktx.com*), were not available during this study.

Our evaluation is concerned with the usefulness of each software in daylighting design application. We focused on the ability of a non-expert designer to learn and run the programs and on the capacity of the software to model a real building that an architect might design. Many buildings designed today are not the simple box or cube with a limited number of rectangular apertures which are often used in validation studies and software development (for example, Aizelwood et al. 1998 and Spitzglas et al. 1985).

A survey of architectural firms (Hattrup 1990) discovered that architects were interested in using daylight in their buildings, tended to explain daylighting to the client as an aesthetic rather than energy issue, and desired to have computer software which could predict the daylighting performance of their designs. In this context, we looked at the following aspects of each package: the time and difficulty of learning to use the software, the ease of building an input file based on existing CAD drawings and documents, the capacity of the input file to describe complex geometries, the run time, the accuracy of the illumination level predictions and the accuracy of the rendered visualization.

Research Background

Daylighting prediction software is often reviewed as a subset or feature of lighting design software or energy simulation software, although recently there has also been some attention paid to these programs as visualization software (Novitski 1992, 1993). Additionally, articles on the performance and features of individual software packages appear regularly in the lighting press, computer graphics publications and architectural journals. (Dubiel et al. 1995; Mahoney 1994; Sullivan 1996; Ward 1990). The Illuminating Engineering Society of North America (IESNA) publishes an annual software survey in *Lighting Design + Application* (IESNA 1997), an extensive, broad matrix which categorizes the features of each package, including price, addresses of vendors and computer hardware requirements.

Technical information addressing the mathematical simulation approaches, the specific algorithms and validation of these programs is largely beyond the interest and expertise of most architects and lighting designers and does not assist them in choosing or appropriately using daylighting software in practice. Such technical papers are regularly published in conference proceedings from SIGGRAPH and the Journal of the IES. A glimpse into the range of technical conference papers is offered by Ian Ashdown's radiosity bibliography at *dream.leeds.ac.uk/ cuddles/rover/abs-ian2.htm*. Ashdown has also published more popularized articles which bring the conference results to a broader public (for example, Ashdown 1993, 1996).

There has been very little published comparing the daylighting programs to each other, and nothing to date which focuses on potential application in design practice. The only comparative study we have found which addresses both Radiance and Lightscape (Khodulev & Kopylov 1996) is available on the internet (*rmp.kiam1.rssi.ru/articles/pals/*). This study investigates the capabilities of Radiance, Lightscape and Specter through simulation of a cube with a single point light source and a series of rooms with various electric light sources. Of the three, Radiance was rated the highest for comprehensiveness of local model and accuracy, while Specter produced the highest quality images. Lightscape was ranked poorest of the three in most categories, with significant accuracy problems. Lightscape, however, was ranked with the best user interface for interactivity of the three programs.

A recent conference paper (Aizelwood et al. 1998) presents a study from the IEA Task 21 validation program investigating the accuracy of Radiance, Genelux and SuperLite. Simulations using these three software packages were compared to data sets developed with extremely simplified physical models (a sidelighted room and a toplighted courtyard) measured in artificial skies. Within these highly controlled comparisons, the three software packages delivered close and accurate predictions of illumination levels.

Project Methodology

This background summarizes the context in which this study was developed. We were interested in whether current software packages could be easily and reliably used in design practice and found no literature which addressed this issue. Fundamentally we asked, "to what extent can a designer successfully predict the quantity and distribution of daylight in an unbuilt design and see what the daylighted space will look like?" To ground the evaluation in current architectural practice, we modeled a recent building in San Francisco. The use of an existing building offered two important reference points for the evaluation: the realities of a building design as documented in standard architectural drawings and the opportunity to measure the actual lighting conditions in the building for comparison with the daylighting predicted by the software packages. In addition to simulating the real building in the four software packages, we also constructed and tested the space using a physical model under artificial and natural skies. We chose to include physical modeling as a comparative simulation technique because physical modeling forms the standard practice in daylighting prediction. It is the most likely method to be used by an architect or consultant practicing today and physical modeling has been validated as an accurate prediction technique within specific limits of scale, detail and metering protocols (Baker et al. 1993; Benton 1990; Hopkinson et al. 1963; Love & Navvab 1991).

1022 Natoma: The Example Building

We were interested in addressing both sidelighted and toplighted spaces, as well as finding a building which represents high quality current practice but not extreme or bizarre architecture. The 1993 live-work building at 1022 Natoma Street in San Francisco was designed by Stanley Saitowitz, a well-known and respected designer who works nationally as well as in the Bay Area (Saitowitz 1994). An architectural office occupies the top two floors of the building and receives sidelight through large southeast and northwest windows (Figures 1a and b). The central two-story space, surrounded by a mezzanine, is toplighted through a roof monitor with sloping ceiling planes and triangular glazing. The roof monitor sees light painted parapet walls on all four sides and a small roof access structure to the northwest on the roof. Both the southeast and northwest windows face a nearly open sky dome across neighboring roofs of dark asphalt, although each view has some sky obstruction due to taller buildings a number of blocks away.

Project Methodology as a Controlled Study

While the purpose of this study is to understand the comparative usefulness and accuracy of the software packages in design practice, in retrospect we realized the study was not totally controlled for conditions as found in practice. The authors, although educated as architects, bring more than average expertise in daylighting and computer applications. In addition, to replicate a typical application of the daylighting software in practice, we would have received the architectural drawings of this space, discussed the intended glazing and finish materials with the project architect and modeled the building with no knowledge of how the space actually looks or performs. We would probably design the study to follow that path now. However, we initially selected the space by visiting it in person and our methodology deviated from the ideal at two points: (1) we knew what the actual space looked like, which cannot happen when a building is still in design development and not yet constructed, and (2) the input files were built with post-construction knowledge of the building materials and finishes.

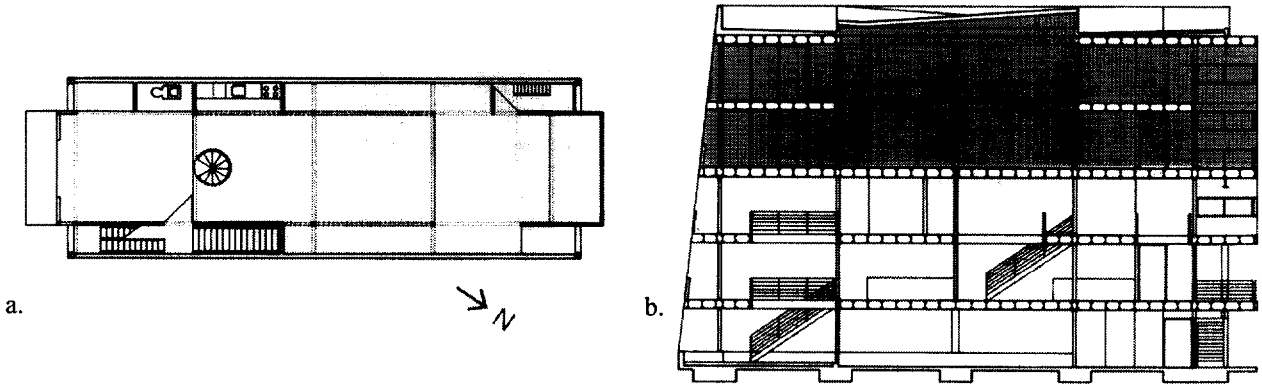

Figure 1. 1022 Natoma: a) Plan of architectural office on top levels, b) Section with study area shaded

We received a regular set of architectural drawings from the architect, but also had a number of photographs of the building interior and exterior to use for material specifications in the input files. After an initial set of runs used to learn the software, we constructed a 1/2"=1'0" physical model to use for comparison as well. In the process of building the model accurately, we measured the glazing transmission and surface reflectances in the actual space. These were subsequently used in the input files for the software packages as well. Sky conditions used in the input files, on the other hand, reflect exactly the way the software and physical models would be used in practice. In each program, we specified date and time and sky condition as the program allowed, with no further knowledge of actual sky conditions brought into the software. Published tables of daylight availability were used to generate illumination values from the physical model measurement as they would be in practice (Robbins 1986, 360-61). Similarly, we had publication photographs of the building interior to use for comparison in generating the rendered output (Saitowitz 1994).

While the input files were probably more accurate than typically possible during the design process, the runs were completed without knowledge of illumination levels in the space or from the physical model predictions. The results from all three procedures (on-site metering, physical model and computer software) were compared once all data had been generated. To the extent that these deviations from the "ideal" method have compromised our results, we estimate that our predictions are somewhat more accurate than might be obtained during the design development phase of a design project because we knew more about the final material selections and characteristics of the building.

Input and Run Characteristics of the Software

For this study, the simulations were run on a 200MHZ Pentium Pro Processor with 128M RAM. A CAD program was used to generate a standard DXF file of the architectural drawings and this was used as the starting point to build the input file for all four software packages. In each program, overcast sky and a clear sky conditions were specified for the times and dates of the real building metering. The overcast sky was simulated for January 26 at 1 pm and the clear sky was simulated for June 29 at 1 pm daylight savings time. We also specified a San Francisco location (38° north latitude and 122° west longitude) and the true building orientation (34° east of north).

Lumen Micro

This software from Lighting Technologies of Boulder, Colorado has for some time been an industry standard for electric lighting design. A daylighting component was first added to the program in the late 1980's and has been upgraded a number of times since. We used Version 7.1 released in 1996 in this study. Version 7.5 was released early 1998. We found the program quick and straightforward to learn and easy to use.

Input Files. The input model is essentially a box with diffuse surfaces and rectangular apertures. Internal partitions and external obstructions are easily defined. An imported DXF file is not used directly, but as a dimensional template to build the input model within the program, which works well. This is displayed two-dimensionally as plan and section and a three-dimensional image can be generated to check the model geometry resulting from this intermediate step (Figure 2a).

The actual geometry of the 1022 Natoma building has been simplified to accommodate some important limitations of this package. Most important for this design, the model is restricted to a four-sided building envelope, which does not allow bays to push out through the walls or roof planes. In addition, all room surfaces and objects within must be rectangular and orthogonal to one another. The canted ceiling surfaces and triangular apertures of the roof monitor could not be modeled accurately and were approximated by a horizontal skylight opening with a shading plane hovering above the glazing. We assumed this "jury-rigged" model is one many architects would try, in that it attempts to include an approximation of top-lighting conditions within the limitations and include the same area of vertical opening, although the glazing plane location has been changed. It is not, however, the only possible accommodation and we do not know whether it is the best possible compromise between the actual building geometry and what is allowed as input in this software. Further insights on this issue were offered by some experiments with the SuperLite input model and are discussed below in the section on comparative accuracy of illumination level predictions. Additionally, the parapets which run on all sides of the roof were not modeled, opening a larger angle of view to the sky than actually exists in the building. Similarly, the side bays or light wells on the southeast side of the building were beyond the capacity of the program, and were modeled as enclosed skylighted "boxes" with interior windows into the main space.

Sky conditions are specified as "clear," "partly cloudy" or cloudy" and the help box states that they conform to the standard sky models of the Commission Internationale de l'Eclairage (CIE). (For explanations of the standard skies see Baker et al. 1993, GL.32; Robbins 1986, 35; Ward Larson 1998, 345-46; for reference algorithms see IESNA 1984).

Running the Program and Output Characteristics. Lumen Micro uses a radiosity approach for calculations which divides the surfaces in the space into small discrete elements. "They assume that light energy is conserved in a closed environment, and they attempt to account accurately for the way in which light emitted or reflected from each surface element is reflected from or absorbed by other surface elements. This involves calculating for each pair of patches a form factor that describes the fraction of the energy leaving one that reaches the other, then the evaluation of energy-balance equations to determine patch intensities." (Mitchell 1992, 156) The radiosity approach, also known as a finite element flux transfer method, is based on the ideal diffuse reflections from a Lambertian or ideally matte surface from which luminance is reflected identically in all directions (Ward Larson 1998, 625). As a result, the calculation procedures model all surfaces as perfectly matte with no specular characteristics.

Lumen Micro is able to produce numerical data quite quickly and offers a number of options for display. The renderings take somewhat longer to generate —the image shown in Figure 6b required

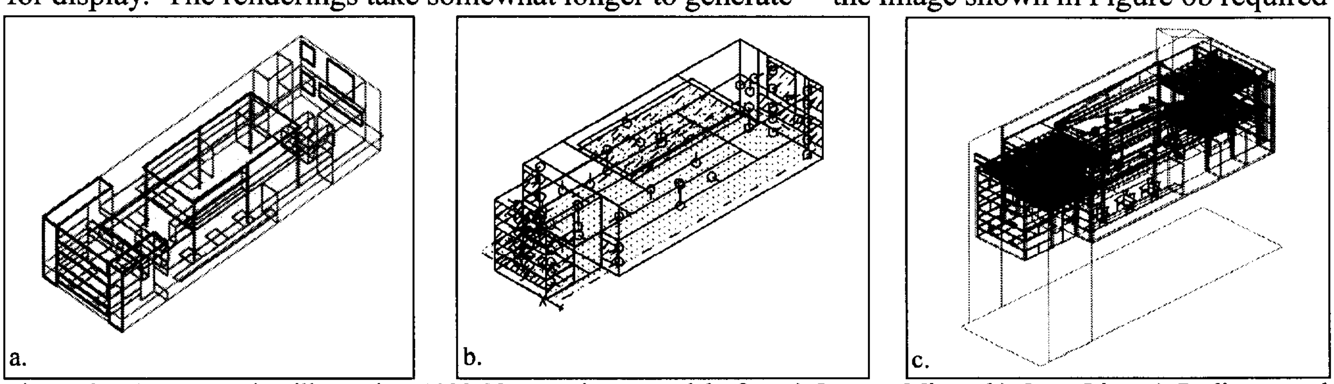

Figure 2. Axonometrics illustrating 1022 Natoma input models for: a) Lumen Micro, b) SuperLite, c) Radiance and Lightscape.

approximately one hour. The program in this version crashed often for us, in spite of friendly and able technical assistance from Lighting Technologies. As discussed below, we were concerned about the quantitative results from our runs and the technical staff at Lighting Technologies were willing to review our input models and perform the runs themselves as a check on our process. The output provides numerical tables of illumination levels, isocontour maps in plan (Figure 3a) and can map illumination levels onto plan, section or elevation and perspective drawings. As a result of the radiosity calculation approach, rendered interior perspectives can be specified for a number of viewpoints without recalculating.

SuperLite

SuperLite IEA 2.0 is a public domain software using a radiosity-based calculation, updated since its development in 1985 by both Lawrence Berkeley National Lab (LBNL) and various European centers. SuperLite and Radiance are included in the Adeline 2.0 package (Advanced Day and Electric Light New Environment), which is a product of the International Energy Agency (IEA) Task 21 initiative and provides an internal CAD modeler (Erhorn et al. 1998). The Superlink program included in Adeline is designed to provide input for advanced thermal analysis software such as DOE2, TRNSYS and BLAST from the SuperLite simulation, which makes it a potentially valuable program for evaluating total energy impact of daylighting, something awkward and difficult to do from physical model results.

Input Files. The input model is created through the Adeline package, with a DXF file converted to meet the SuperLite conventions or the model can be built directly in Scribe Modeler within Adeline. The model is basically a box with all surfaces orthogonal and defined as ideally diffuse. The number of surfaces, windows, visual obstructions and nodes are limited, although each version released increases the number allowed. Similar to Lumen Micro, the roof monitor and the southeast window wall of 1022 Natoma could not be modeled as they are in the real building, since the geometry does not allow the canted roof planes of the monitor and only allows two exterior shading objects. Our initial solution for the roof monitor was the same as we used in Lumen Micro — an horizontal opening to the sky with a shading plane hovering above and no roof parapets (Figure 2b). The southeast wall was especially

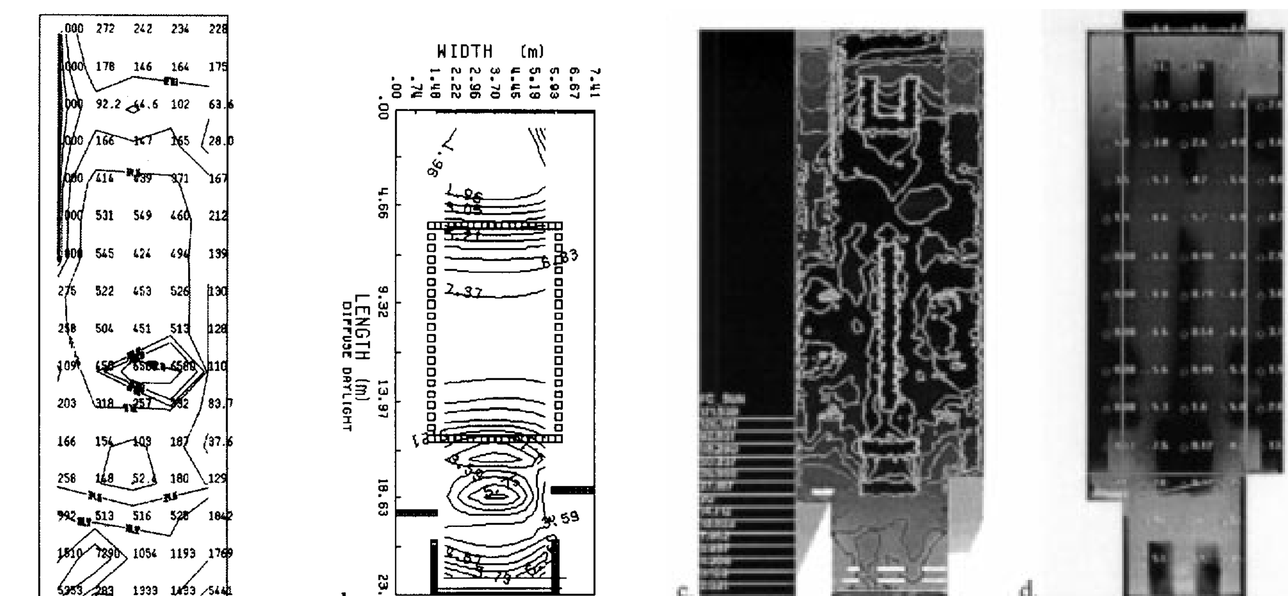

Figure 3. Plan output illustrating clear sky isoilluminance contours for June 29, 1pm from: a) Lumen Micro in fc, b) SuperLite in klux, c) Radiance in fc, with the color scale not readable in black and white reproduction, d) Lightscape in fc grid points and isoilluminance contours as rendered background.

limited by the allowed number of exterior shading objects, so that the side bays disappeared, resulting in fewer obstructions than these windows actually see. A graphic display of the model allows one to check the inputs before proceeding. Sky condition can be input as uniformly overcast, CIE standard overcast and CIE clear sky (with or without sun), or with much more specificity (for example, specific irradiance and luminous efficacy data). (Please see the sources referenced above for CIE standard sky information.)

Running the Program and Output Characteristics. SuperLite uses radiosity to quickly produce illumination levels or daylight factors. The runs are almost immediate and generate both tabular data and illumination levels graphed in three different formats, including a plan with contours (Figure 3b), a section through the room and a three-dimensional data plot. The output can be transferred to Radiance for a rendered image, although in architectural practice the image would not be useful. The rendered image illustrated in Figure 6a took about two minutes to render in Radiance. We found that SuperLite is especially valuable in the quickness of its numerical feedback on a given design, allowing the designer to quickly conduct parametric evaluations and multiple comparisons between design approaches, aperture designs, reflectances and glazing transmissions.

Radiance

Radiance was initially developed in the mid-1980's by LBNL for use on UNIX work stations to explore lighting simulation techniques other than the flux exchange methods such as radiosity which were in use by other simulation programs. In this study, we initially used version 2.5 in Adeline and changed to version 3.0 in Unix once it was available in 1997. Radiance has an active users group internationally, connected through the Radiance web page, and a well-documented and peer-reviewed technical development (Ward Larson & Shakespeare 1998). Available as a PC application within Adeline, Radiance can be linked to the program Radlink and produce hourly daylighting input to the thermal simulation programs mentioned above in the SuperLite section.

Input Files. The input model uses a DXF file, which allows all the geometric and material complexity of a real building to be accurately included in the simulation (see Figure 2c). For the 1022 Natoma building this meant that the butterfly roof, the parapet walls, the roof access shed, the triangular glazing in the monitor, the multiple apertures and recessed bays of the southeast were all modeled as designed and built in reality. Within the office space, the joists, the desks, the computers, bookcases and luxo lamps were part of the simulation model. In fact, many more specifications for material and optical properties are available in this program than the standard architect or lighting designer will be able to use. Sky conditions can be set to clear sky (with or without sun), CIE standard overcast or uniform overcast, as referenced above in the Lumen Micro section. These can be further modified with additional parameter settings (such as turbidity factors), most of which are beyond the capacity or need of the typical designer but allow a researcher to control the sky description quite carefully. The sky description can also be completely supplied by the user.

Running the Program and Output Characteristics. Radiance uses a hybrid approach of Monte Carlo (stochastic) and deterministic ray tracing techniques to simulate the direct, specular indirect and diffuse indirect illumination components of daylighting (Ward Larson 1998, 494-95). "Ray tracing is an elegant systematization and extrapolation of an idea that goes back at least to Brunelleschi's early perspective studies... The basic strategy implemented by ray-tracing algorithms is to consider the picture plane as a fine grid of pixels placed between the viewer's eye and to send a ray from the eye through each pixel to the scene." (Mitchell 1992, 154) "In *light-forwards ray tracing*, light is followed from the light sources to the final measurement areas. In *light-backwards ray tracing* (as in *Radiance*), each view ray is traced from the point of measurement to the contributing light sources." (Ward Larson 1998, 629)

Run time depends on the indirect lighting component of the calculation, with length increasing as the accuracy of the associated settings are increased. A balance is struck by the user between the time and the accuracy and quality of the simulation. The rendered perspective in Figure 6d required nearly 24 hours for completion. A useful feature is that accurate numeric calculations can be run separately and much faster than the fully rendered perspective image. Output is available in tabular form, mapping of illuminance and luminance values onto any view of the space in contours or false color, and rendered perspective views (Figure 3c). As a result of the ray tracing simulation approach, each view is calculated and rendered individually, making a walk-through or animation virtually impossible in a reasonable time frame on a desktop computer.

Lightscape

Lightscape has been developed by Lightscape Technologies of San Jose, California to provide rendered images of both electrically lighted and daylighted spaces. Initially available in Unix for use on high end graphics machines such as Silicon Graphics or Sun work stations, the program is now widely advertised to architects and lighting designers for use on a PC. We tested version 3.0 in this study, although 3.1 is now available. Lightscape Technologies offers libraries which include lighting fixtures, carpet samples, stone samples and furniture elements from major manufacturers, as well as generic objects and materials.

Input Files. The input model is a DXF file (such as illustrated in Figure 3c above) or a 3D Studio file, which can be checked to make sure all surfaces are oriented correctly. This input strategy, like Radiance, allows the entire complexity of the architecture to be included in the simulation model. The 1022 Natoma geometry and even furniture could be included, limited primarily by the time available to create the CAD drawings. Before the run, all surfaces which are daylight apertures are identified, which serves two purposes. First, it reduces calculation time, since the program doesn't look for light sources in non-identified surfaces. Equally as important, this step avoids light leak artifacts in the rendered output which result from using non-precise 3D positioning input DXF files (for example, 3D modeling programs like 3D Studio will not necessarily position all planes with precise closure like CAD programs such as AutoCAD do).

The color and associated reflectivity of surface materials and glazing are assigned with a menu driven slider bar for color or imported with texture maps. Three more slider bars are used to set "transparency", "refractive index" and "smoothness" which are used in the ray tracing portion of the calculations. Sky condition is set with a slider that moves between "clear" and "cloudy" in units of sky coverage. According to the Lightscape web site, these are calculated according to IES RP-21 "Calculation of Daylight Availability" (*www.lightscape.com*; IESNA 1984).

Running the Program and Output Characteristics. Lightscape uses a radiosity approach as discussed above to produce the quantitative illumination predictions and offers the additional capability of ray tracing to better render the contribution of specular materials. The run time depends on the degree of rendering accuracy desired and can vary significantly. The rendered image in Figure 6c was produced with both the radiosity and additional ray tracing steps of the software and took approximately 8 hours to render. The program can produce a grid of illumination levels on any surface (Figure 3d illustrates a plan view), luminance values for any surface defined in the model, false color views and perspective renderings.

An important asset of the radiosity calculation technique is that viewpoints can be easily changed without the necessity to recalculate the scene, but without the ray tracing option as part of the rendering. This allows walk throughs and animations to be developed with a single calculation and rendering step, but bases both the visual and numerical output on radiosity calculations only.

Comparative Results

The software output were compared with real building conditions and physical model predictions in two important aspects: illumination levels on a work plane throughout the space and visualization of the daylighting conditions within the space.

Illumination Levels

We were interested in the capability of each software to predict illumination levels under two typical San Francisco sky conditions: a summer clear sky with sun and a winter overcast sky. San Francisco also has clear winter skies and overcast or foggy summer skies, which perhaps identifies a future extension of this project to collect additional on-site data.

The results from the real space, the physical model and the four software packages have been graphed for comparison in the charts below (Figures 4a and b). The readings graphed were taken at 7' inside the southwest side wall from the southeast to the northwest and the lower level. This location was chosen to represent both the impact of the side-lighting and the top-lighting without engaging the obstructions of the bookcases and spiral staircase in the center of the bay and to determine the illumination levels close to the drafting tables without too much obstruction from individual desktop arrangements. We did not select this location to purposefully favor or place at a disadvantage any software program or the physical model.

On-Site Measurements. For the real building illumination measurements, we selected times and dates as close to the summer and winter solstice as possible (taking into account the El Niño-driven winter rainstorms, holiday schedules and a flu epidemic). We also tried to find real skies as close to CIE standard skies as possible, although the difficulty (or impossibility) of doing this is well documented (Gillette et al. 1984; Jongewaard 1993; Kittler & Ruck 1984; Navvab et al. 1984). The on-site monitoring was completed with a Campbell Scientific 21X data logger and LiCor 210S photosensor located and leveled on the roof parapet for exterior reference measurements of horizontal global or total sky illuminance. Simultaneously a LiCor 210S photosensor mounted on a tripod at 30" height was located on grid points within the office space and illumination levels recorded by hand.

Physical Model. We included the use of a 1/2"=1'0" physical model of the space as part of this study, principally because physical models are typically used in practice and will be the design tool replaced by advanced computer simulations. Physical models measured in calibrated artificial skies are also a

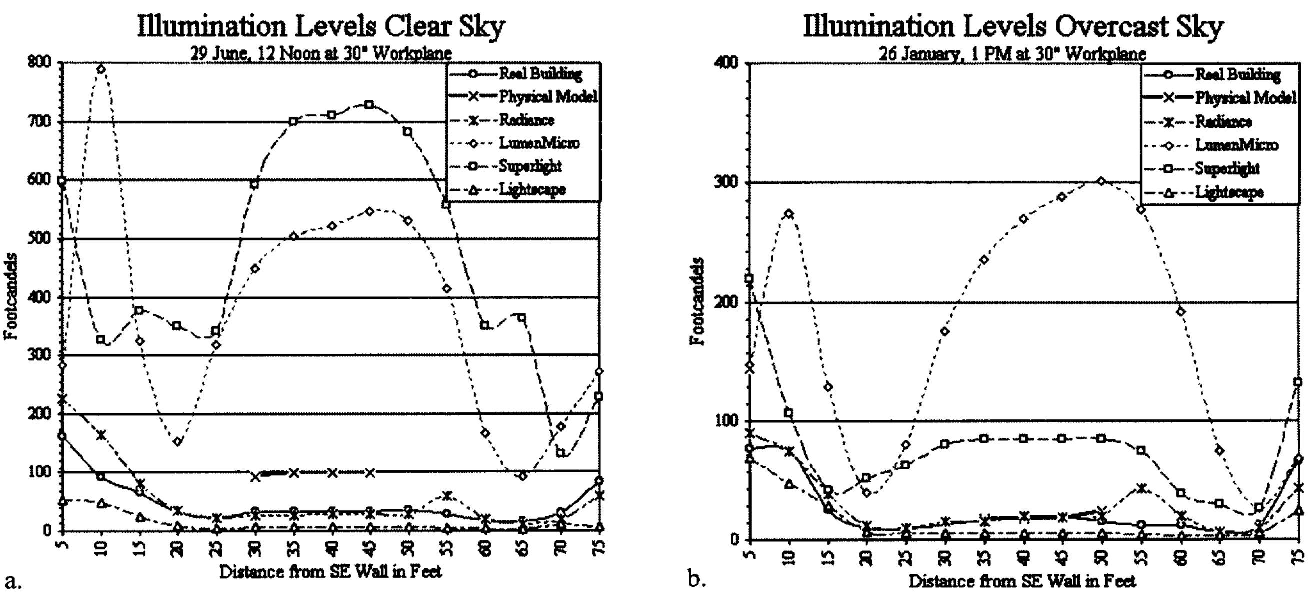

Figure 4. Comparative illumination levels: a) clear sky, b) overcast sky.

common reference for validating illumination predictions by computer software (Aizelwood et al. 1998; Jongewaard 1993; Love & Navvab 1991; Spitzglas et al. 1985; Ward 1990). The model was tested in the mirror box artificial sky in the Building Science Lab at UC Berkeley for overcast skies and under natural clear skies on the roof of Wurster Hall on the Berkeley campus, using LiCor 210 photosensors and a Campbell Scientific 21X data logger. The clear sky readings were taken in November, not at the time or date of the real building monitoring or the simulations. This is a typical problem with physical models used under clear natural skies. Although the technique has been proven inaccurate (Love & Navvab 1991), we used a sun dial to orient the building to match June 21st sun angles as many architects do when faced with the need for a clear sky prediction at the wrong time of the year and as suggested by a number of manuals (see, for example, Schiler 1987, 50-56). This resulted in a distorted orientation with the southeast windows facing the gravel roof instead of the southeastern sky. Daylight factors were calculated from the model results and daylight availability charts for San Francisco (Robbins 1986, 360-61).

Clear Sky. Comparative illumination levels for clear sky with sun conditions are presented in Figure 4b above. The clear sky readings in the building were taken on June 29th at 1 pm Pacific Daylight Time (12 noon solar time) and normalized to a 10,000 fc clear sky with sun. The software predictions were also calculated for that time, date and a clear sky with sun using the sky algorithms in the programs. The physical model results were calculated for June 21st and 12 noon solar time. (The full clear sky illumination contours in plan for the four software packages are illustrated above in the software descriptions.)

The data show significant variations in illumination levels between simulation tools and between some software and the measured data. We are confident of the real building monitored data and find that the Radiance predictions follow closely, with an overestimation at the southeast window (225 fc versus 162 fc, approximately 40% high), a smaller underestimation at the northwest window and an unexplained bump in the data at 55 feet from the southeast wall. The physical model overestimated the internal levels (100 fc versus 33 fc or approximately 3 times too high), undoubtedly due to the reflected light off the gravel roof during testing. Lightscape predicts a curve similar in distribution to the measured data, but underestimates the illumination levels throughout at only 20% of the measured (for example, 6.6 fc versus the measured 33 fc at 35 feet from the southeast windows).

The real surprises were the predictions 10 to 15 times too high generated by Lumen Micro and nearly 20 times too high generated by SuperLite, both of which have been validated (Jongewaard 1993; Spitzglas et al. 1985). Both the shape of the sectional distribution and the quantities are so unmatched to the real space measurements and are so similar between the two software packages, that we have to conclude the compromised input geometry has significantly impacted the accuracy of the prediction for his particular model. This is exactly why a real building reveals limitations that generic example spaces do not. Neither Lumen Micro or SuperLite show these limitations when used with the kind of space they are capable of modeling: rectangular rooms with rectangular apertures (Aizelwood 1998; Sptizglas et al. 1985). Nevertheless, many practitioners in architecture are moving away from the conventionally rectangular space and aperture and software packages will be expected to handle geometries far more radical than that presented by the Saitowitz office.

A Small Study of the Input Model as Source of Inaccuracy. In response to discussions with Bill Carroll of LBNL and Davidson Norris of Carpenter Norris Consulting, we were interested in exploring in more detail the impact of the "jury-rigged" input model. We ran a set of SuperLite comparison runs for the same clear sky condition and time using the following input model variations, all built within Scribe Modeler in Adeline: a fully glazed opening the size of the raised monitor opening with no exterior shading object (Figure 5a), the initial approach with an horizontal glazed opening with a hovering shading plane at 18" above the glass (Figure 5b), an exterior butterfly-shaped shading object over an horizontal glazed opening (Figure 5c), and raised ceiling plane with a vertically glazed monitor 18" high (Figure 5d).

The illumination levels predicted for locations 7'-0" in from the southwest wall and directly beneath the monitor area are revealing. For the input Figure 5a, the illumination ranged from 623 fc in the diffuse daylighted areas to 7,380 fc in the large direct beam resulting from the unshaded skylight. The input models which use the exterior shading object, both horizontal plane and butterfly (Figures 5b and c) produced very similar results, with intensities under the monitor ranging from 519 fc to 813 fc under the butterfly shading object. These are consistent with range of illumination levels initially predicted by the horizontal plane as shading object and graphed in Figure 4a for SuperLite and we can conclude that both shading objects produce about the same illumination levels in spite of their difference in shape. These values are still much too high in comparison to the 23 fc to 35 fc measured in the real building. The most interesting data are from the raised roof and vertical glazed monitor (Figure 5d). These ranged from 39 fc to 71 fc under the monitor, values much more in the ballpark of the real space. We think these can be understood as a more reasonable prediction which is still too high as a result of the missing parapet walls on the roof in this model.

These results identify a more closely defined source for the problems with the input model as we initially constructed it. The open horizontal skylight produces the very high illumination levels (expected from direct solar penetration on a clear summer day), both horizontal shading objects (flat and butterfly shaped) produce illumination levels similar to those graphed in Figure 6a, still higher than measured by a factor of 10 or more. However, the use of a monitor with vertical glazing rather than a horizontal skylight with exterior shading produces illumination levels within the same order of magnitude, if still higher than in the measured space. We would attribute the inaccuracy to the lack of the parapet walls on the roof in the input model rather than the monitor configuration itself. The large difference between the use of both exterior shading objects and the vertically glazed monitor configuration would indicate that the shading object calculations (or methods of definition) are not serving the SuperLite predictions well. This points to a potential source of the inaccuracies in the Lumen Micro predictions as well, although we are still unable to construct a monitor with vertical glazing as a Lumen Micro input file to cross check. A finding which may relate is presented in a Lumen Micro validation study (Jongewaard 1993), in which the shading factors calculated for the sky patches seen through the apertures are found to be inaccurate. Both findings would indicate the need for future research on the calculations of shading objects in these two radiosity-based programs.

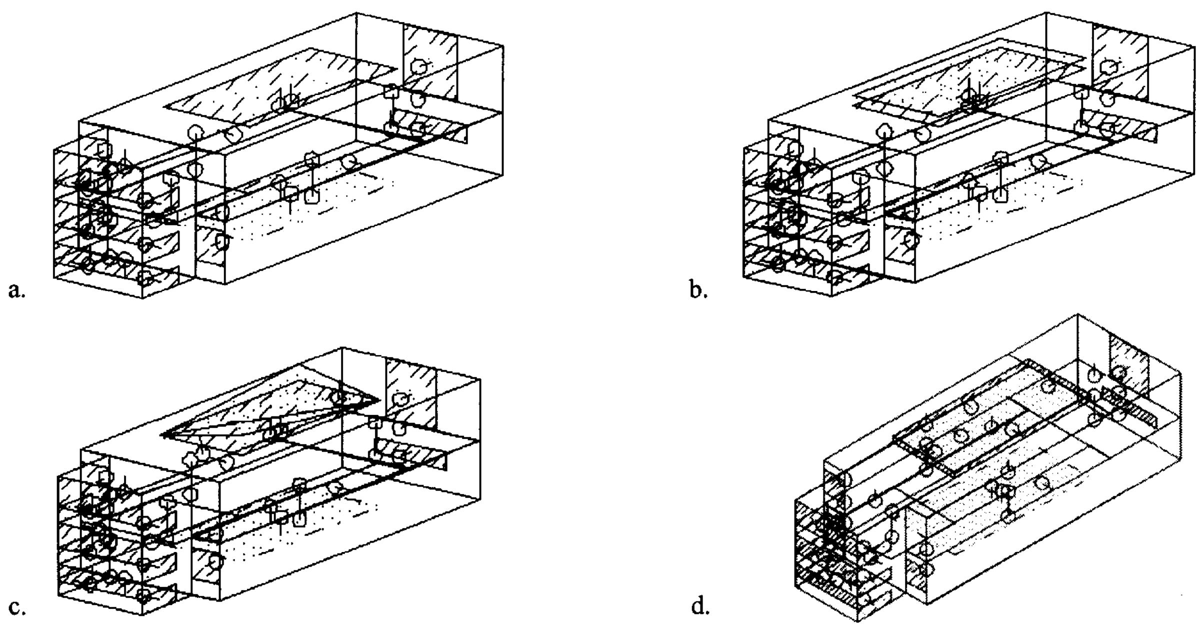

Figure 5. SuperLite input models with: a) horizontal glazing and no exterior shading, b) horizontal glazing and horizontal exterior shading objects, as in the initial input and graphed in Figure 6a, c) horizontal glazing and exterior butterfly shaped shading object, and d) raised monitor roof and vertical glazing.

Overcast Sky. Comparative illumination levels for the overcast sky conditions are presented in Figure 4b above. The overcast sky readings in the building were taken on January 26th at 1 pm Pacific Standard Time and normalized to a 1200 fc sky. The software predictions were also calculated for that time, date and sky condition. The physical model results were calculated for January 21st at 1 pm. During the monitoring of the real space, the sky appeared fully overcast as we measured the interior, but the clouds began to break shortly after we completed the measurements and it is unlikely that the real sky matched the CIE overcast distribution for the period of measurement. This reaffirms the difficulties of using a natural sky as a base line for data comparison and indicates that, for the overcast sky conditions, the physical model metered in the mirror box artificial sky provides a better base case (see also Love & Navvab 1991).

The data variations in illumination levels between simulation tools and the measured data are less exaggerated than the clear sky results, however, the Lumen Micro and SuperLite results still display significant deviations (up to 10 times too high for Lumen Micro and 4 times too high for SuperLite) which we ascribe to the input model compromises described at the beginning of the paper. The Radiance predictions again match the measured data closely, although the same increase in the illumination level predicted is again evident at 55 feet from the southeast wall. It appears in both the clear sky and overcast sky runs in Radiance but it does not show up in the measured data nor is it predicted in the other software results. The physical model predictions are almost identical to the measured data — the four data points from the model are hard to distinguish in the chart because the points so closely overlay the Radiance and real building data. These results are consistent with past experience in the use of physical models and mirror box skies for overcast conditions. Lightscape shows a distribution curve similar to the measured data and comes closer than with the clear sky predictions, but the illumination levels below the monitor are still significantly underpredicted at only 20-30% of that measured (5 fc versus 25 fc at 35 feet from the southeast windows).

Renderings and Visualization Capabilities

In contrast to expectations of daylighting software a decade ago, today's designers are looking for highly realistic renderings of the designed space with which to speak to their clients. Rendering software used in most architectural offices, such as 3D Studio, do not create physically accurate lighting predictions but rather supply a choice of generic sources (flood, spot, ambient etc.) and let the designer deploy them until the image looks "good." This kind of software is ubiquitous in architectural practice, used as rendering tools for presentations and is excellent at creating false stage sets to present building designs.

"For the architect, however, the question of rendering light effects accurately is not merely one of achieving some *n*th degree of realism on screen or on a printed version of the design. In the first place the architect's concern is not only with the image, but goes through and beyond it to the final building. So the on-screen image needs not only to have its own realism, but to be related with some exactitude to the lighting specification... that is proposed for the project in hand." (Zampi & Morgan 1995, 140). The challenge for daylighting software is to produce rendered images not only competitive with these packages, but also technically accurate for design evaluation. An accurate rendering enables the designer to check on potential glare problems, patterns of direct beam radiation entering the space, and to select between design options from a visual as well as quantitative standpoint.

Figures 6a-f illustrate the overcast sky renderings from each of the four software packages along with photographs of the physical model and the real space under the same sky conditions. It is clear that Lumen Micro and SuperLite provide such rendered output choices to check the geometry of the input model in addition to the quantitative output which is the main offering. Radiance and Lightscape, in contrast, are powerful visualization programs. In this application, we find that the penumbral shadows in Radiance on the wall and the graduated levels of light along the canted ceiling plane of the monitor are more closely related to the photograph of the real space, while the glossy reflections from the floor are rendered more closely in Lightscape. These subtleties of the graduated shadows are also captured in the model, which one would expect, but the model space will never look realistic with the sensors present and without hours of painstaking construction of scale furniture.

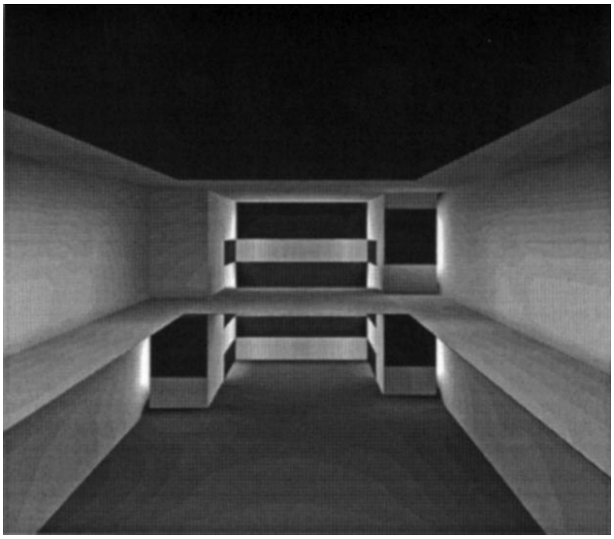

Figure 6a. SuperLite overcast rendering January 26

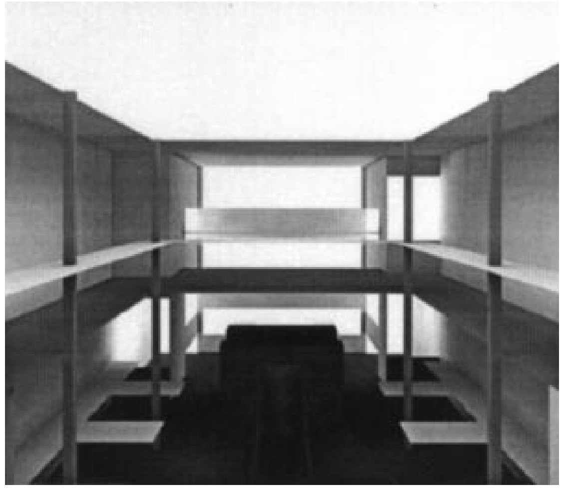

Figure 6b. Lumen Micro overcast rendering January 26

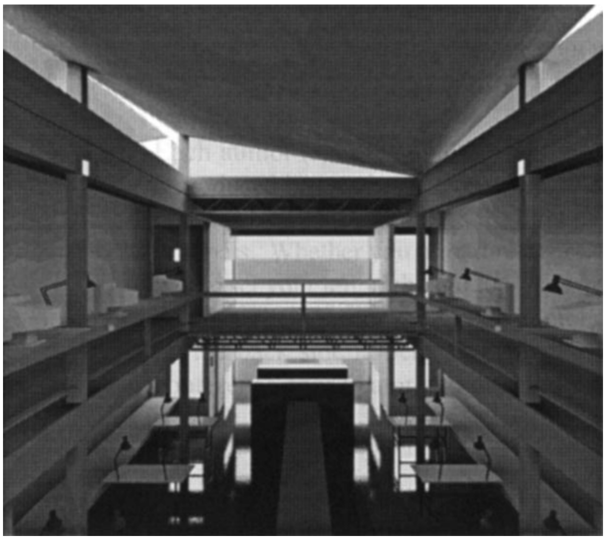

Figure 6c. Lightscape overcast rendering January 26

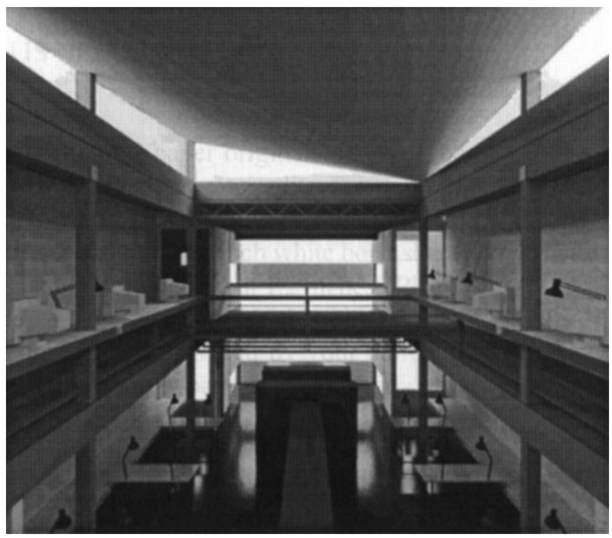

Figure 6d. Radiance overcast rendering January 26

Figure 6e. Physical model overcast photograph

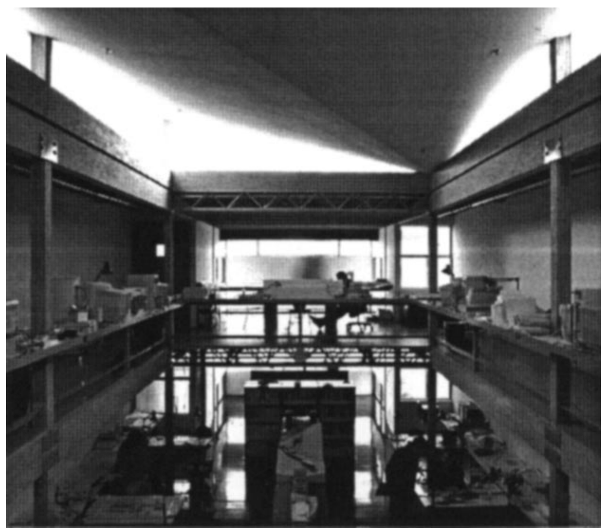

Figure 6f. Photograph of real space January 26

Conclusions

The field of daylighting software has changed completely in the last ten years and is now dominated by a small number of powerful programs, each developed from a different starting point and with slightly different application emphasis. In general, the arguments between radiosity and ray tracing which were so dominate over the last decade have diminished as the major players (Radiance and Lightscape) have opted to use some of each method.

This study used one particular and unique building geometry, although not a radical example, to see what might happen when the world of architectural practice and design begins to use daylighting software. We are especially interested in the practical application of daylighting software and have found, just as in the 1989 study, the ability to model the complexities of real buildings is essential for their daylighting software to be accurate and useful in design practice.

This study is neither a validation exercise nor research into the calculation algorithms of these software packages, but rather focuses on a single case of predictions and monitored data, with all the potential difficulties both can offer in terms of accuracy. The results should be viewed with regard to these limitations. In the quantitative results, this study indicates that the more restrictive an input model is, the more likely a real design will not be modeled accurately in the input state. This means it is less likely that the output will be an accurate prediction of the daylight in the real building.

Both Lumen Micro and SuperLite have been shown to be accurate if the space being modeled matches the limitations of the input model requirements (Aizelwood 1998; Spitzglas et al. 1985). It is also clear that these two programs offer daylighting predictions with objectives other than visualization and rendering. For Lumen Micro, the daylighting analysis is essentially a supplement to a powerful industry-standard electrical lighting software and is appropriate in generic daylighting applications such as sidelighted offices. SuperLite can be used in Adeline to generate inputs for sophisticated thermal analysis programs. However, when Radlink connects a Radiance rendering to these thermal analysis programs smoothly, SuperLite may cease to have a clear function in the Adeline software package. SuperLite is also used as a validation tool and a base case for comparison in situations where the model geometry can be completely trusted.

The "high end" programs Radiance and Lightscape offer an interesting comparison. Radiance has proven in this study, as well as in the Russian study cited, to be much more accurate in predicting illumination levels than Lightscape and is the program of choice if accuracy is important. Accuracy is important if the software is being used to address energy use issues, electrical lighting design and architectural design decisions. In contrast, in Lightscape the lack of specificity in describing the sky algorithms adds to our concerns about its accuracy raised by the study. However, Radiance does not yet have a reasonable user interface and requires a great deal of time and training to use well. A number of projects are underway to address this problem with Radiance (Janak 1998; Papamichael et al. 1998, Schmidt 1995). Until they are widely available, Lightscape offers many advantages. The ease with which Lightscape can be learned, the constant updating of input and translation functions to accommodate other software used in practice, and the relative speed with which renderings can be produced are very attractive features to architects and lighting designers.

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