Final Report

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Project Title ....Improving Lighting and Daylighting Decision Making to Facilitate the Design of Energy Efficient Buildings

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Abstract

SCE and other California utilities have been developing tools for the Savings by Design program that help architects, engineers, lighting designers and consultants to meet or exceed increasingly stringent Title 24 requirements. Building decision makers lack easy and quick means to assessing daylight and electric lighting performance during decision making on key parameters that not only impact energy use but greatly affect the quality of the luminous environment. These factors include window size and orientation, glazing type, luminaire types and layout, reflectance of interior surfaces, etc.

To properly consider daylighting and electric lighting performance, decision-makers often need to use lighting simulation tools, which compute work-plane illuminance and often surface luminance values. However such tools often have long learning curves and are time consuming to use, thus pressuring design costs. There is a clear need to provide options for assessing quantitative and qualitative aspects of lighting and daylighting designs that beat Title 24 but in a more cost effective manner than the conventional use of simulation tools.

The main deliverable of this project is the Radiance Image Database (RID), a tool that allows users to quickly and easily assess the effects of key parameters on the daylight and electric lighting performance of various lighting and daylighting designs, for various space types. Supporting both quantitative and qualitative performance assessment, RID can help improve lighting and daylighting decision making to facilitate the design of energy efficient buildings.

RID is based on a large database of results from computer-based simulations, in the form of images and statistical data. The simulations were performed for various space types and lighting/daylighting systems, varying parametrically the values of key lighting and daylighting parameters. The simulations were performed using the Radiance lighting simulation and rendering software. RID consists of two modules: a Daylighting module and an Electric Lighting module.

The Daylighting module includes simulation results for a small office space in the Los Angeles area. The simulations were performed for numerous combinations of selected values for key design parameters that affect daylighting performance, such as window orientation and size, glazing type and shading, as well as key context parameters, such as time of the day/year and sky conditions.

The Electric Lighting module includes simulation results for five space types (classroom, small office, large open office, big box warehouse and small retail store), each considered with alternative lighting designs that exceed the requirements of the Title 24 energy code. The values of key parameters that affect electric lighting performance, such as wall and ceiling reflectance, were varied selectively, based on space type and electric lighting system.

RID has a Web-based user interface that allows quick and easy access to the contents of the database, supporting side-by-side comparison of alternative designs and scenarios to facilitate evaluation. The Web-based user interface makes RID accessible through a common web browser, like Netscape Navigator and Internet Explorer. RID is available at http://gaia.lbl.gov/rid.

This final report documents the process of creating the RID and provides a discussion of the most prominent issues and technical challenges of the project. It also discusses areas for further work towards expanding the initial version of RID and improving its usability and usefulness.

Introduction

Building decision makers lack easy and quick means to assessing daylight and electric lighting performance during decision making on key parameters that greatly affect the luminous environment and the associated energy requirements, such as window size and orientation, glazing type, luminaire types and layout, reflectance of interior surfaces, etc.

To properly consider daylighting and electric lighting performance, decision-makers often need to use lighting simulation tools, which compute work-plane illuminance and often surface luminance values, based on room geometry and optical properties of materials and light sources. The more advanced simulation tools also produce output in the form of rendered images of the simulated environment, which support qualitative performance assessment. Proper assessment of quantitative and qualitative performance requires the use of advanced lighting simulation tools, like Radiance (http://radsite.lbl.gov).

Radiance is one of the most advanced lighting simulation tools, and has unique capabilities in accurately modeling daylighting. It can model environments of arbitrary geometric and photometric complexity. Radiance produces images that are photometrically accurate and supports various display forms to facilitate quantitative and qualitative assessment. However, the Radiance software is hard to learn, and time-consuming to use as well. The time requirements for the use of the Radiance software include both the preparation of the Radiance model and the duration of the simulations.

Depending on geometric/photometric complexity and desired level of detail, the preparation of a Radiance model can take from a few hours to several days. A Radiance model is usually developed incrementally, using iterative simulations to make sure that the modeling process is proceeding correctly. Simulation time requirements vary from a few seconds to many hours or even days, depending on the desired image size quality/accuracy, the geometric and photometric complexity of the scene and the available computing power.

Today's powerful desktop and work station computers can run Radiance simulations very effectively. During the last few years significant effort has been put into porting the Radiance simulation engine from UNIX to Windows for the development of Desktop Radiance (http://radisite.lbl.gov/deskrad). In addition to the Radiance simulation engine, the Desktop Radiance software includes links to AutoCAD, a popular commercial CAD package, four libraries of materials, glazings, luminaires and furniture and a simulation manager that helps users manage multiple simulations.

While Desktop Radiance makes the use of the Radiance engine much easier and faster, it still takes significant time for use during the design process, in a design-iteration mode, i.e., evaluating many alternative combinations of values for key lighting and daylighting parameters towards meeting design objectives. As a result, Radiance is mostly used to model designs that are almost complete, rather than to guide design decisions related to key parameters that affect lighting and daylighting performance.

The objective of this project is to develop an easy to use graphical tool that will allow building designers to quickly assess the impact of key daylighting and electric lighting parameters in commercial buildings, also demonstrating energy-efficient lighting practice. It utilizes the power of the Radiance outputs but without the time and cost of generating conventional images. The strategy to achieving the project's objective is based on the development of a large database of pre-calculated results from multiple parametric Radiance simulations (varying the values of key parameters that affect daylighting and lighting performance) and the development of an intuitive user interface that allows access to the database. The resulting tool is the equivalent of a virtual simulator, which instantly provides very high quality output, for many alternative combinations of values for key lighting and daylighting parameters.

The project has two main Tasks, one focusing on key parameters that affect daylighting performance in a single space type and the other focusing on alternative lighting designs for five different space types.

This Final Report contains a detailed description of the scope and accomplishments for both Tasks. The report also includes a description of the main deliverable, which is a tool that combines the results of both tasks into a Web-based application, currently referred to as the Radiance Image Database (RID). Finally, the report includes a description of the most prominent issues and challenges, as well as a list of areas for further work towards expanding the initial version of RID and improving its usability and usefulness.

Task 1: Daylighting

Since there are many key daylighting design parameters, such as window size and orientation, glazing type, reflectance of interior surfaces, etc, as well as many contextual parameters, such as sky conditions, time of the year, etc, that affect daylighting performance, the scope of the daylighting task for the initial version of the database was limited to a single space, i.e., a small office space with a desk and a chair.

One of the main issues addressed was the computation time requirements for the Radiance simulations. The issue was addressed through a preliminary study on computational time requirements for various options for image sizes and quality. The image size issue was also relevant to the user interface. After testing several combinations, we decided on a combination of image size and quality that takes between 2 and 4 hours for each simulation.

Another major issue was related to the design of the small office space and the key parameters and values to be consider for the initial version of the daylighting module. To increase the value of the resulting tool, we looked into opportunities to relating to other studies that could offer complementary information. The Windows group at LBNL, in partnership with the University of Minnesota and others is developing a new book on commercial glazing systems. The work for that book includes parametric evaluation of the energy performance of an office building, varying key daylighting parameters.

After reviewing the work that was done for the book, we concluded that the office space and parameters considered were very much appropriate to meeting the objectives of our project. We then decided to follow the space specifications and parametric options used in the book, which would make the book and the tool complementary to each other, increasing the value of both.

The small office space considered is 10ft wide and 15ft deep, with a 9ft high ceiling, a 1ft high plenum and one window located on the 10ft wide wall. The Los Angeles area was considered for all daylighting simulations. The details of the parametric simulations are described below, along with the output parameters of the Radiance simulations.

Window size and placement

Four window-to-wall ration (WWR) values were considered, following the Commercial Glazings book options: 15%, 30%, 45% and 60%. The size and position of the window also follow the Commercial Glazings study and are listed in the table below:

WWR	Window width	Window height	Window sill height
15%	4.0 ft	4.5 ft	3.0 ft
30%	6.0 ft	6.0 ft	3.0 ft
45%	9.0 ft	6.0 ft	3.0 ft
60%	10.0 ft	6.0 ft	1.8 ft

Glazing parameters

Five different glazing types were considered, following the Commercial Glazings book options, which represent the major classes of glazings commonly used in commercial applications. The glazings and their transmittance and reflectance values were as follows:

Name	Transmittance	Reflectance
Clear	80%	14%
Tinted	38%	40%
Reflective	10%	41%
Low-e	34%	19%
Selective Low-e	59%	21%

Shading options

Three different shading conditions were considered, following the modeling in the Commercial Glazings book:

1. No shading
2. Overhang
3. Overhang and vertical fins

The overhang width was the same as the window width. The overhang was assumed flush with the top of the window.

The height of the vertical fins was the same as the window height. The vertical fins were assumed flush with the left and right sides of the window.

The depth of the overhang and vertical fins varied with WWR, following the modeling of the Commercial Glazings book for the Los Angeles area, as follows:

WWR	Overhang depth	Vertical fin depth
15%	2.25 ft	2 ft
30%	3 ft	3 ft
45%	3 ft	3 ft
60%	3.5 ft	3 ft

Reflectance of interior and exterior surfaces

The reflectance values for the walls, ceiling and floor were fixed at 50%, 70% and 20% respectively. The reflectance of the ground was assumed at 20%.

Window orientation

The orientation of the window, combined with the date and time, determine the relative position of sun and the sky luminance distribution for a given location. Four orientations were considered for the window: North, East, South and West.

Day of year

Three days were considered, representing the four different seasons of the year:

1. December 21 (Winter)
2. March 21 (Spring and Fall)
3. June 21 (Summer)

Time of day

Three times of day were considered, representing different periods of the day:

1. 9:00 AM
2. 12:00 Noon
3. 3:00 PM

Sky conditions

Two sky conditions were considered: overcast and clear sky conditions, following the standard CIE overcast and clear sky luminance distributions.

Computed parameters

The computed parameters include the direct Radiance output in the form of images and additional design data that were computed from the quantitative information that is included in the Radiance output files.

Design Data for Radiance Image Data Base

The content of the data base is a series of visual and numerical data that are generated for each scenario. The data elements are designed to provide different insights into the daylighting performance of each scenario. There are two primary types of data displays. One shows illuminance on the work-plane which corresponds to conventional design guidance for measured light levels from sources such as the Illuminating Engineering Society. The second shows luminance on room surfaces, which provides insights into whether a room will appear to be dim or bright, and on the potential for visual comfort or discomfort.

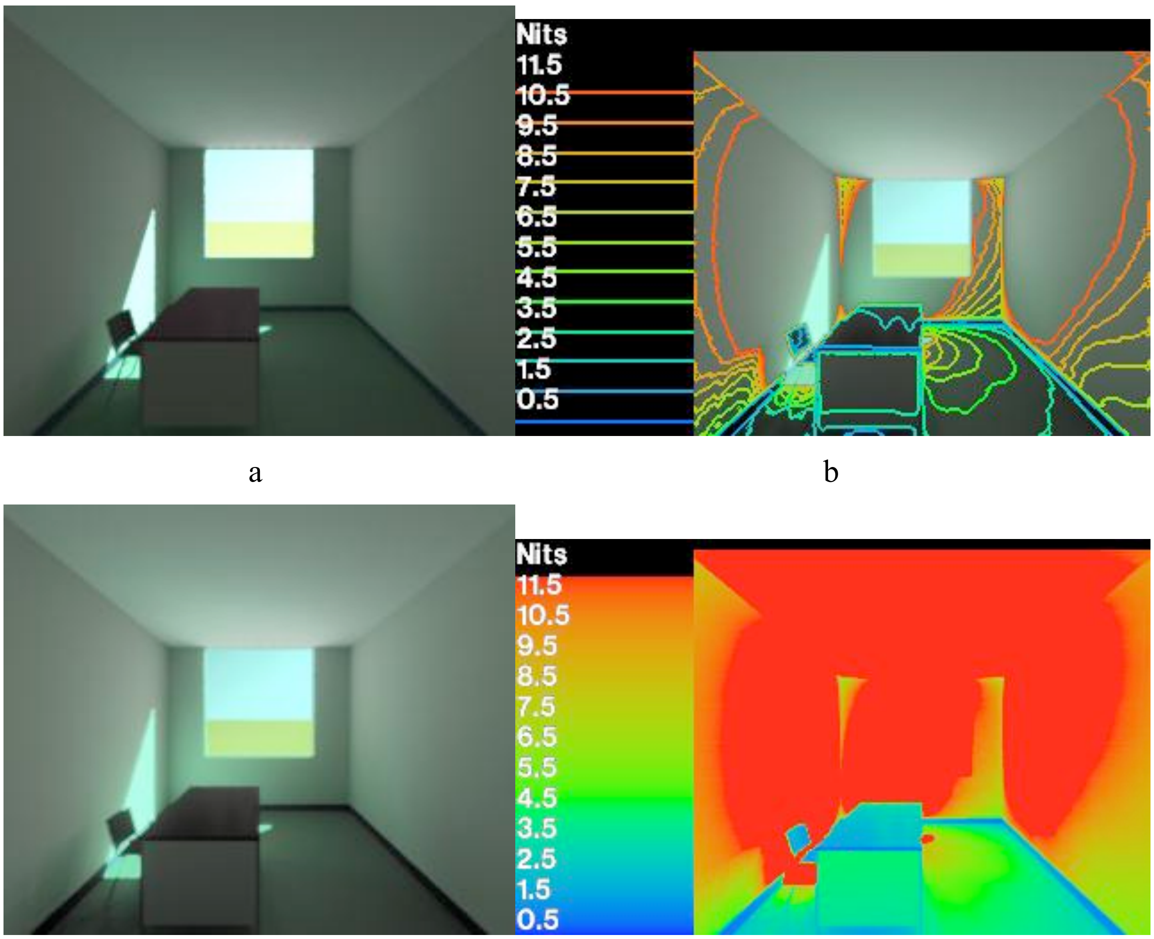
Images

Three images were computed for each scenario, i.e., combination of design and context parameter values:

- Perspective from the rear wall, showing luminance values
- Perspective from the side wall, showing luminance values.
- Plan, from above, showing work plane illuminance values.

Each image was converted for display in four different ways (Figure 1):

- Camera exposure, using the average luminance in the scene.
- Human exposure, considering the sensitivity of the human eye.
- Camera exposure with superimposed contour lines of luminance or illuminance
- Camera exposure in false color, indicating magnitude of luminance or illuminance.



a b

c d

Figure 1. Perspective of th small office space used for the Daylighting Module in camera exposure (a), camera exposure with iso-contour lines (b), human exposure (c) and false color display (d).

Additional parameters

The following parameters were also computed through Radiance simulations, which hold information about the actual luminance and illuminance values:

- Minimum work plane illuminance.

- Average work plane illuminance.
- Maximum work plane illuminance.

The computation of the statistical information on minimum, maximum and average values for work plane illuminance was based on a dense grid calculation, which, however, produced many low values at the grid points that work plane was cutting through furniture. This produced confusing images of work plane illuminance and introduced errors in the statistical computations. To resolve the issue, we developed routines to exclude the low values from the images and the computations of the statistical information.

Task 2: Electric Lighting

The Electric Lighting task focused on the consideration of contemporary lighting designs that exceed Title 24 requirements, for five space types:

- Classroom
- Small office
- Large, open office
- Big box warehouse
- Small retail store

The spaces for the electric lighting module were modeled with complete furniture and detailed modeling of the electric lighting systems. The geometric complexity and number and type of light sources significantly increased simulation times in many cases to more than 60 hours per simulation. Considering the available resources for the project, only selected combinations of key lighting parameters were considered, based on space type and lighting system.

To provide added value to this work, as in the daylighting Task, we looked for opportunities to relate the electric lighting Task to other studies that could offer complementary information. Two studies were considered: the Advanced Lighting Guidelines and the Lighting Know How series. However, some space specifications (e.g., dimensions, furniture layout) did not accurately represent California and the lighting systems were not up-to-date. The designs were updated with input from Lisa Heschong and James Benya, with support from the California Energy Commission (CEC). The design and major considerations for each space are presented below.

Two sky conditions were considered for the Electric Lighting dataset: night sky and partly cloudy sky at 12:00 noon, on June 21, in the Los Angeles area. The main windows were oriented north, to provide uniform daylight and avoid solar control issues that would further complicate the design and simulations without being directly related to performance of the electric lighting systems, which was the focus of the project for the initial version of the database.

All images for the electric lighting simulations were produced in the same four display types as for the daylighting module:

- Camera exposure, using the average luminance in the scene.
- Human exposure, considering the sensitivity of the human eye.
- Camera exposure with superimposed contour lines of luminance or illuminance
- Camera exposure in false color, indicating magnitude of luminance or illuminance.

The following parameters were also computed from the Radiance output files:

- Minimum work plane illuminance.
- Average work plane illuminance.
- Maximum work plane illuminance.
- Installed lighting power density.
- Used lighting power density (for scenaria with dimmed light sources).

The computation of the statistical information on minimum, maximum and average values for work plane illuminance was based on a dense grid calculation, which, however, produced many low values at the grid points that work plane was cutting through furniture. This produced confusing images of work plane illuminance and introduced errors in the statistical computations. To resolve the issue, we developed routines to exclude the low values from the images and the computations of the statistical information.

Classroom

The classroom space is 32ft by 30ft and was considered with three alternative lighting systems: 4ft troffers, 4ft pendant direct and 8 ft pendant direct/indirect. The space was considered with two different ceiling heights: 9ft for the troffer design and 10.5 ft for the direct and direct/indirect designs. The furniture arrangement represents a typical California classroom, with windows on the North side and clerestories on the South, shaded with an overhang (Figure 2). The transmittance of the glazing is 50%.

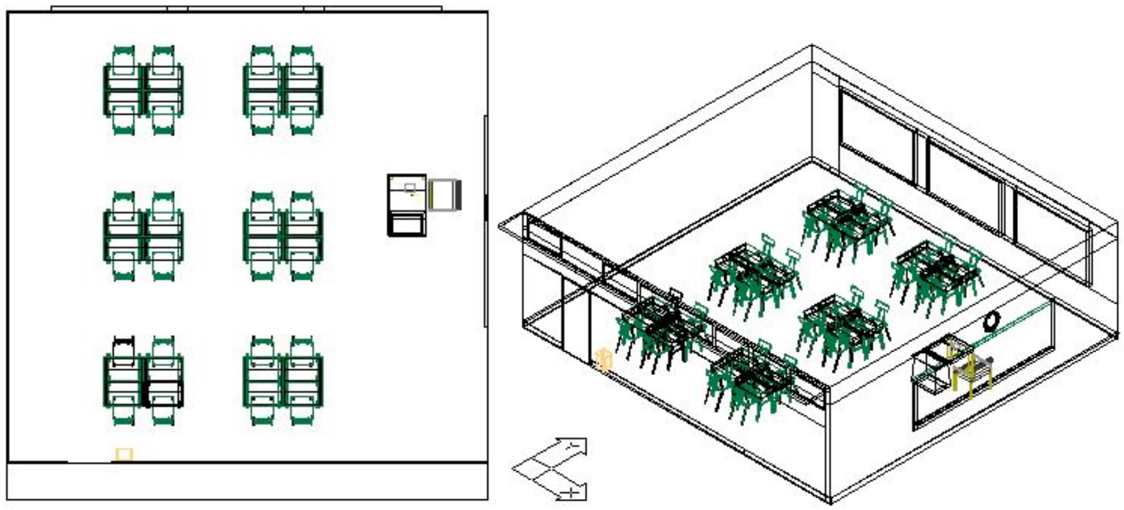


Figure 2. Plan and axonometric of the classroom space.

The troffer system represents a common low-end option and was considered with three rows of fixtures, each of which can be switched on and off individually. Several on/off combinations were considered to support assessment of the effects of manual control by the teacher. The pendant systems represent higher-end options and were considered in full and daylight-based dimmed output, to support assessment of the effects of dimming on the overall environment.

The camera position for the perspective view represents the view of a student seating at the rear center of the room. The chalkboard was considered in black, green and white colors, to better understand and allow assessment of the effects of chalkboard color on visibility.

Two wall reflectance values were considered for the troffer and the direct direct/indirect designs: 60% for the whole wall and 60% for the wall up to a height of 7ft and 90% above 7ft. Two ceiling reflectance values were considered for the direct/indirect system: 80% and 60%. The ceiling reflectance was set to 80% for the troffer and the direct systems. The wall reflectance was set to 60% for the direct system.

Two images were computed for each scenario, i.e., for each combination of parameter values (Figure 3):

- Perspective from the rear wall, showing luminance values.
- Plan, from above, showing work plane illuminance values.

Figure 3. Sample renderings of the classroom space with two different electric lighting designs.

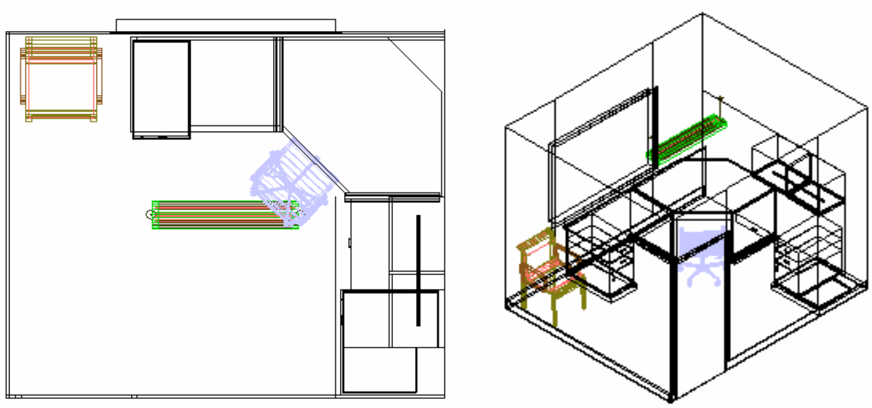
Small office

The small office space is 10ft by 12 ft with a ceiling height of 9.5ft and one window on the 12ft wall. It was considered with two different furniture layouts (Figure 4). One of the furniture layouts was considered in two colors, light gray and brown wood, to allow assessment of the effects of furniture color and reflectance on the overall luminous environment. Three lighting layouts were simulated: the troffer and tasklight, the indirect pendant with tasklight, and a portable scheme utilizing the torchiere, a desklamp, and tasklight.

Two images were computed for each scenario, i.e., for each combination of parameter values:

- Perspective from the side wall, showing luminance values.
- Plan, from above, showing work plane illuminance values.

Sample images are shown in Figures 5 and 6.



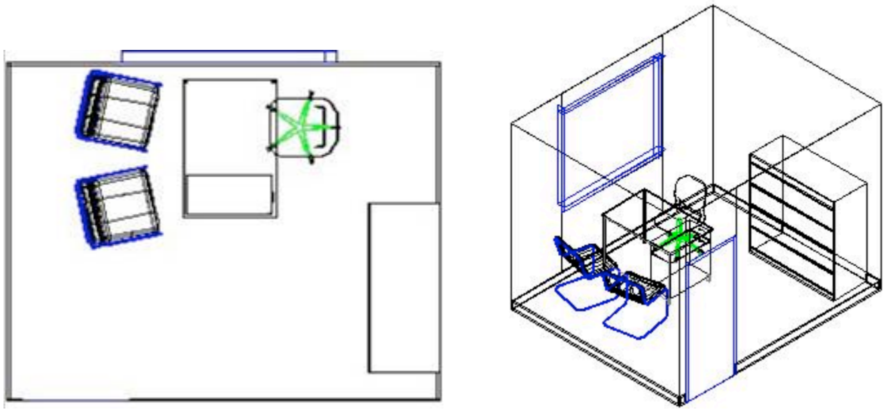


Figure 4. Plan and axonometric of the small office space with two furniture layouts.

Figure 5. The small office space with the portable lighting design during night (left) and day (right) times.

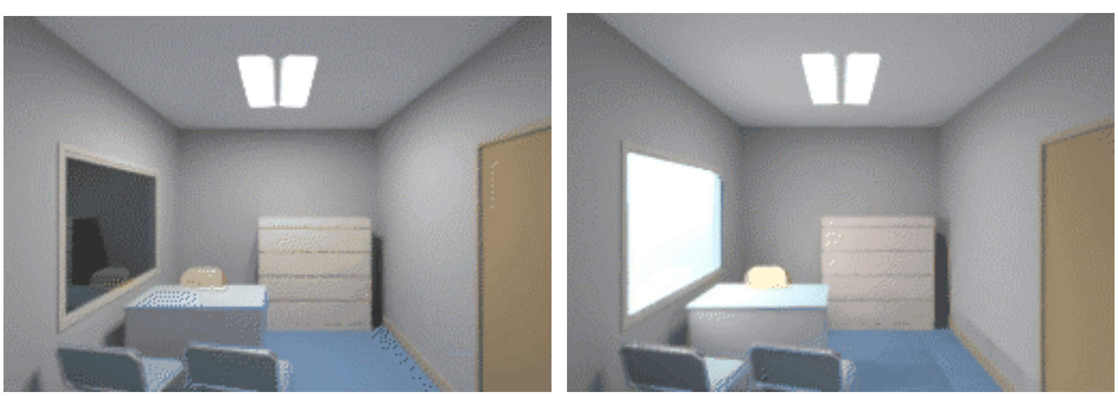


Figure 6. The small office space with alternate furniture layout, direct lighting system, and night and day times.

Large Open Office

The open office space is 40 ft by 35 ft with a ceiling height of 10 ft and two windows on the north-facing wall (Figures 7, 8 and 9). The cubicles are 8 ft by 8' each, with partition heights of 5 ft. The ceiling, wall, and floor have reflectance values of 89%, 50%, and 17%, respectively. It was considered with one furniture layout with varying partition reflectance values of 20% and 50%. There are two luminaire layouts: direct (troffer) system with tasklights, and indirect pendant system with tasklights.

Two images were computed for each scenario, i.e., for each combination of parameter values:

- Perspective from the side wall, showing luminance values.
- Plan, from above, showing work plane illuminance values.

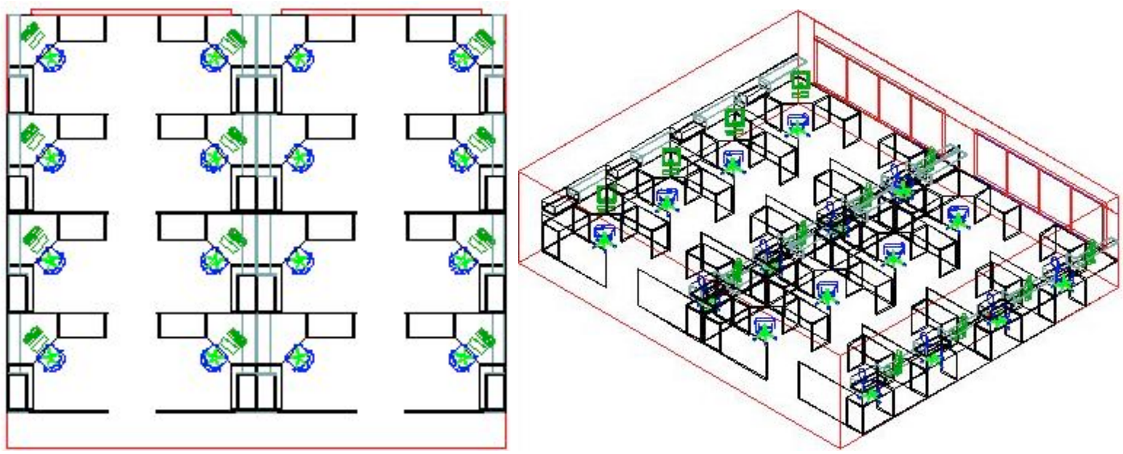


Figure 7. Plan and axonometric of the large open office space.

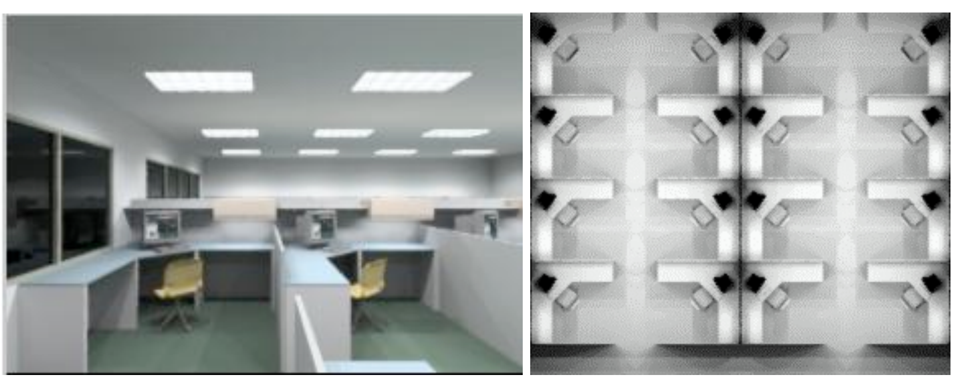


Figure 8. Sample open office rendering with troffers full on, perspective and plan.

Figure 9. Sample open office rendering with troffers off in first row and dimmed in second, perspective and plan.

Big box warehouse

The big box warehouse is 60 ft by 64 ft, with a ceiling height of 25 ft (Figures 10 & 11). There are no windows, however, there are two openings representing the entry and emergency exit. The ceiling, wall, and floor have reflectance values of 80%, 66%, and 22%, respectively. It was considered with one merchandise layout with varying cardboard box reflectance values between 20% and 40%.

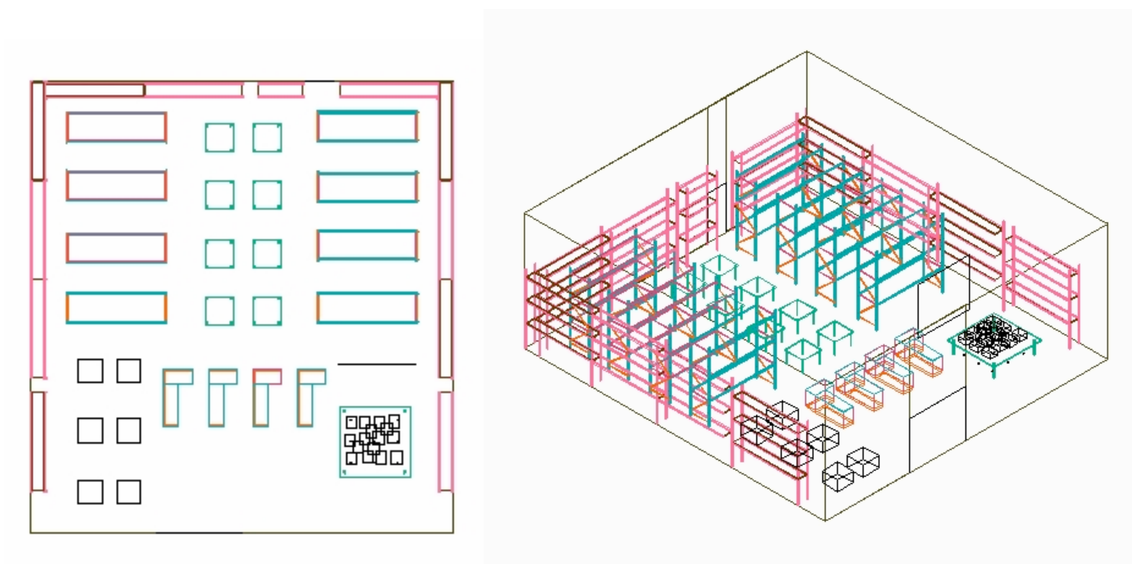


Figure 10. Plan and axonometric of the warehouse space

Figure 11. Sample renderings of the warehouse space.

Small Retail Store

The small retail store is 20 ft by 36 ft, with a ceiling height of 12 ft (Figures 10 and 11). There are no windows, however, there are two openings representing the entry and emergency exit. The ceiling, wall, and floor have reflectance values of 80%, 66%, and 22%, respectively. It was considered with one merchandise layout with varying cardboard box reflectance values between 20% and 40%.

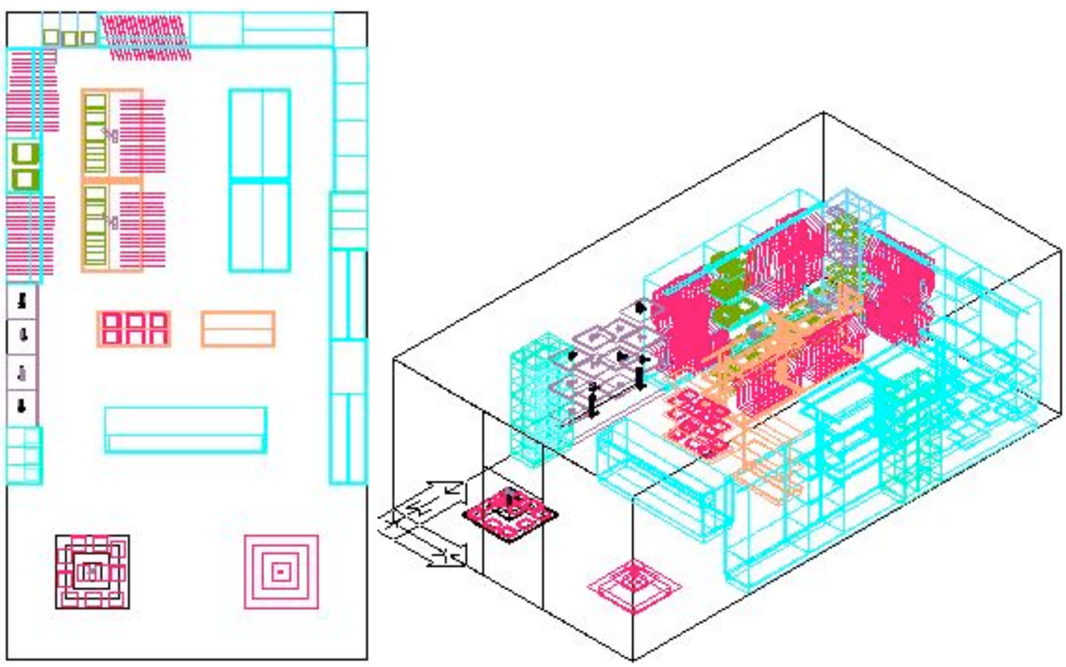


Figure 10. Plan and axonometric of the small retail space.

Figure 11. Sample renderings of the small retail space.

The Radiance Image Database (RID) Tool

To accommodate the very large number of images and allow for easy expansion of the tool, it was decided to use a Web-based interface that allows access to the database through the Internet, using a standard Web browser, like Netscape Navigator and Internet Explorer.

The user interface design had several objectives. It had to be easy and intuitive, allow comparison for perception of value, allow simultaneous quantitative and qualitative displays, and be uniform for both modules and all space types. It also had to fit into the low end of screen resolutions. All of the above were considered early on for the determination of the image dimensions, prior to starting the Radiance simulations.

The design of the user interface is targeted to a display of at least 800x600 pixels, which is a minimum for most of today's computer displays. The user interface consists of three main frames: a header frame and two identical in design frames that allow side-by-side comparison of different scenarios or of the same scenario in different display modes. Two copy buttons at the bottom of the screen allows instant copying of one frame to the other to support quick setting of a base for side-by-side comparison. Several screen shots of the RID tool are shown in Figures 12 through 15.

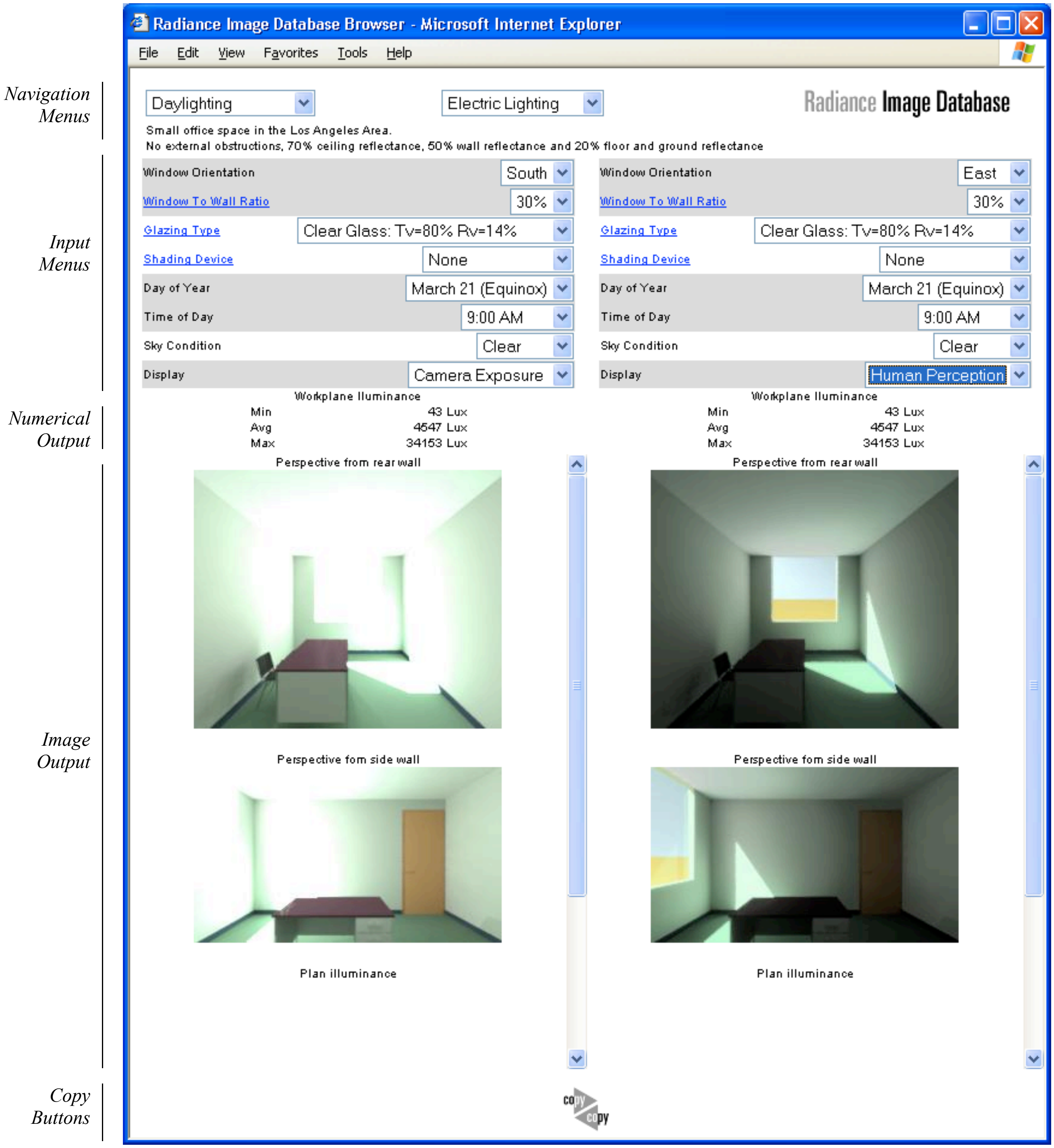


Figure 12. Screen shot of the Daylighting module, showing the small office space in Camera Exposure display (left) and Human Sensitivity display (right), along with annotation indicating the four major user interface areas.

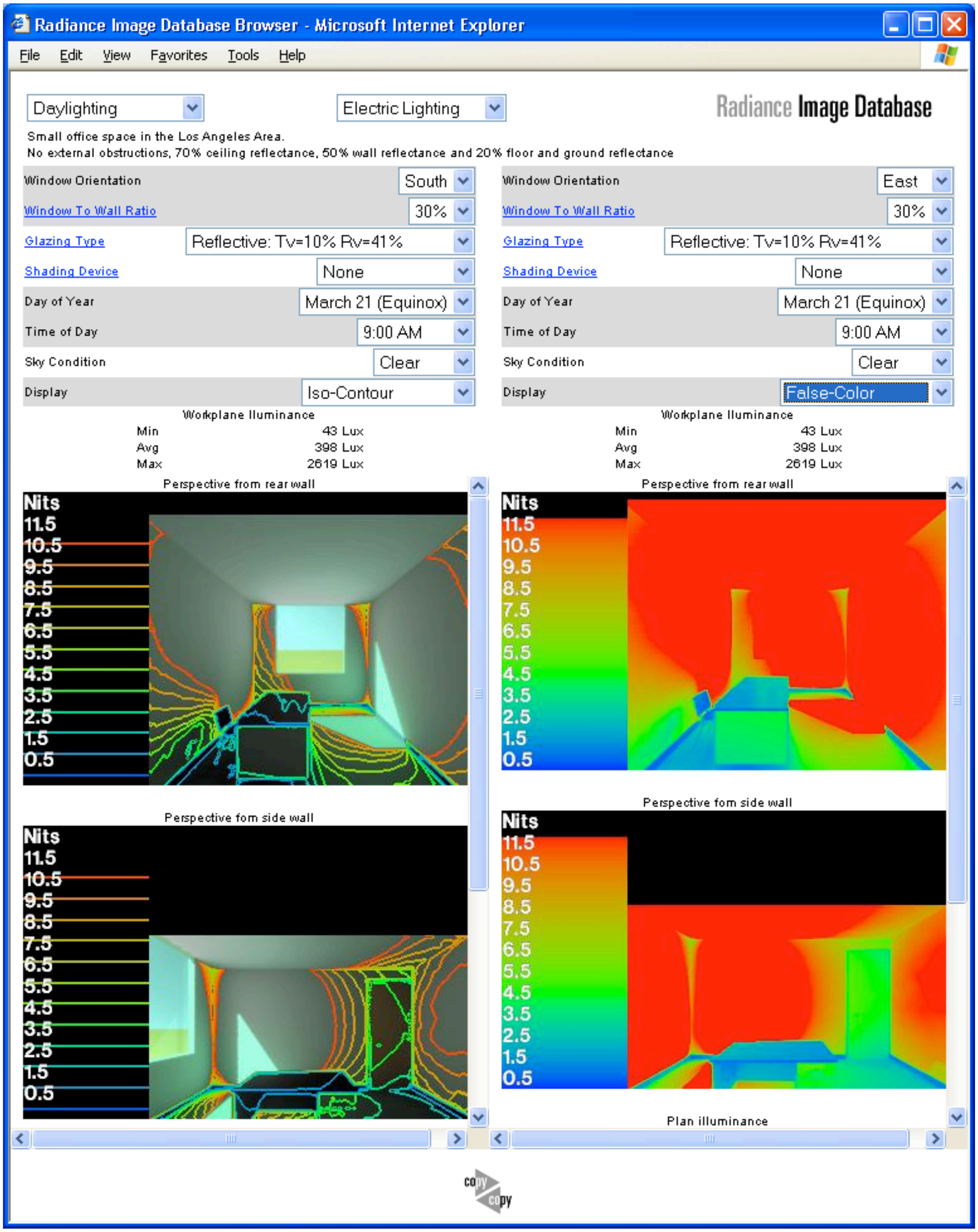


Figure 13. Screen shot of the Daylighting module, showing the small office space in Iso-Contour display (left) and False Color display (right).

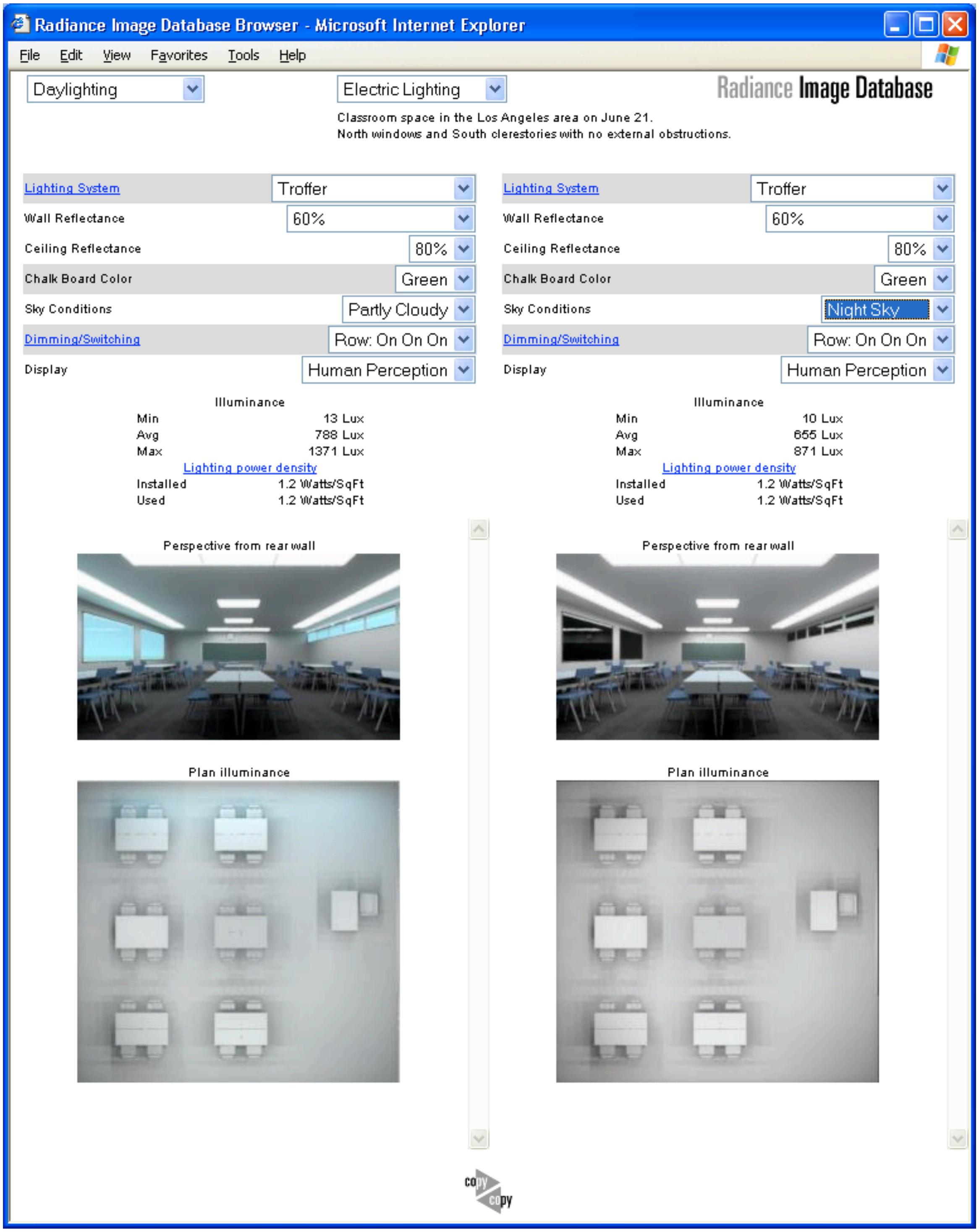


Figure 14. Screen shot of the Electric Lighting module, showing the classroom space with troffer luminaires in daytime (left) and nighttime (right).

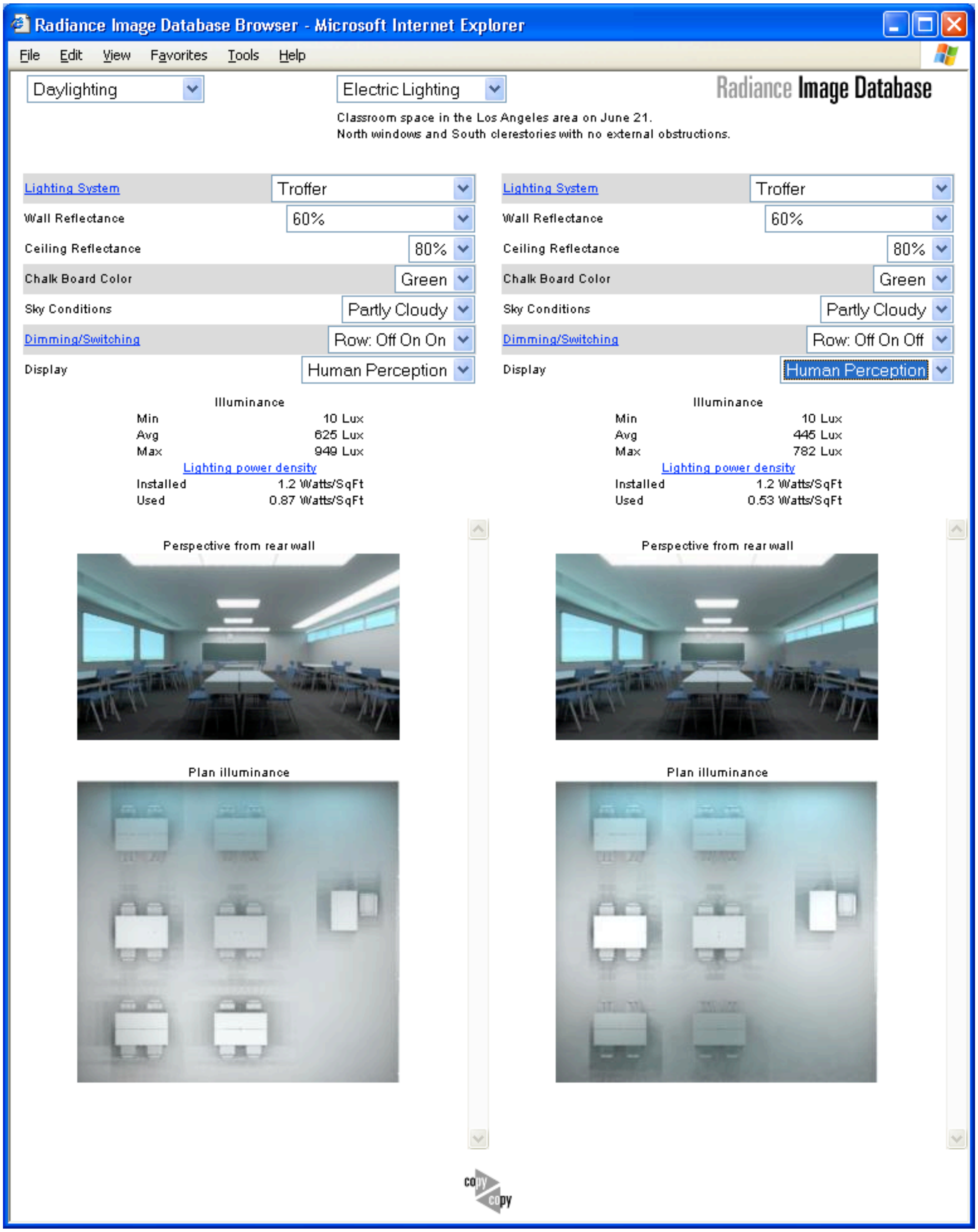


Figure 15. Screen shot of the Electric Lighting module, showing the classroom space with different rows of the troffer luminaires switched off

Major issues and challenges

The development of the Radiance Image Database required resolution of several major issues and overcoming of several major challenges. The project required a very large number of Radiance simulations, and it was difficult to accurately estimate the time requirements for each simulation for the production of high quality images. This made planning very difficult with respect to determining the scope of the simulations. To accommodate consideration of all five spaces, we had to compromise on the level of modeling detail and be selective in the electric lighting parametric simulations.

The computational system that was put together for the simulations is quite unique and, although it has proved quite successful, it required continuous monitoring and maintenance, which included several periods of down time for replacement of hardware and software. In its current state, the system appears to be stable and effective. Moreover, we now have a much better understanding of computation time requirements for different geometric complexities and types of lighting systems. This will allow us to generate more accurate estimates for future simulations and better plan future projects on expanding the initial version of the Radiance Image Database.

One of the main issues that were addressed was the display of the resulting images. Although Radiance computes the whole range of luminance and illuminance values, computer monitors are limited with respect to the range that they can display. While the Radiance image viewer allows for dynamic change of the image exposure, we had to use a single exposure for the generation of the images that were included in the database. We decided to use an exposure based on the average luminance of each image (camera exposure) and generated a series of displays that were adjusted for the sensitivity of the human eye to better support the qualitative assessment of the lighting conditions in the space.

The "camera exposure" display is the equivalent of the image that would be generated by a photographic camera, with an exposure that corresponds to the average brightness of the scene. In this display, the luminance distribution of the scene is mapped linearly to the intensity display range of the output device. The limited intensity range of computer screens may result in images with over and/or under exposed areas.

In the "human exposure" display, the luminance distribution of the scene is mapped in a non-linear way to the intensity display range of the output device. The mapping algorithm takes into account the sensitivity and adaptation of the human eye and the resulting image is closer to how humans would perceive the scene.

The selective approach to the parametric simulations for the electric lighting part of the database resulted in increased complexity of the user interface, because it required dynamic lists of parameters and value options for each electric lighting space.

To manage the many thousands of images of the database (Table 1), we used a file naming scheme that uses a code to reflect the value combinations for all key parameters for each image. This has allowed us to use the filing system as a database management system, which is very effective for the browsing of the images.

Table 1. The number of images and storage requirements for the various sections of the current version of RID.

Module	**Number of Images**	**Disk Space (KB)**
Daylighting		
- Small Office	51,764	267,000
Electric Lighting		
- Classroom	1,004	10,000
- Small Office	544	5,000
- Open Office	96	1,000
- Warehouse	16	218
- Small Retail	36	379

Conclusions and future directions

The initial version of RID seems promising in meeting the project's objectives, i.e, supporting quick and easy assessment of the effects of key parameters in lighting and daylighting designs. The user interface seems to very effective in performing comparisons among alternative scenaria, or evaluating a single scenario using different side-by-side quantitative and qualitative output.

The daylighting module allows users to very quickly and easily understand the effect of key daylighting parameters in the Los Angeles area. The electric lighting module demonstrates alternative energy-efficient lighting designs that exceed Title 24 requirements, for five different spaces types. Moreover, it shows the effects of key parameters that affect the luminous environment, as well as the quantitative and qualitative effects of dimming and/or switching of electric lighting fixtures during daytime.

We look forward to getting more extensive user evaluation and expand the Radiance Image Database, considering more locations, space types, fenestration and lighting options, locations, dimming controls, etc., as well as more user interface functionality.

We are also considering the possibility of expanding the functionality of the RID site to allow processing of the actual Radiance images through the Radiance image viewing utilities, which will allow for real-time adjustment of image exposure and feedback on luminance and illuminance values by clicking on any point of the image, or selecting an area of the image for average values.

Finally, we are considering the possibility of "opening" the database so that users can expand it by running additional simulations and saving the resulting images back into the database. This scenario would work by opening up all possible combinations of values for input parameters, as well as allowing the consideration of new values. If the images for a requested combination of input values are already available, they will be displayed just like in the current version of RID. If images are not available for the particular combination, then Radiance could be activated to generate them and add them to the database. The simulations could happen on the user's computer and may take time to complete. The next user, however, that would request the same combination would have the images readily available for display.