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**New Tools for the Evaluation
of Daylighting Strategies
and Technologies**

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Introduction

The use of daylight for the illumination of building interiors has the potential to enhance the quality of the environment while providing opportunities to save energy by replacing or supplementing electric lighting. Moreover, it has the potential to reduce heating and cooling loads, which offer additional energy saving opportunities as well as reductions in HVAC equipment sizing and cost. All of these benefits, however, assume proper use of daylighting strategies and technologies, whose performance depends on the context of their application. On the other hand, improper use can have significant negative effects on both comfort and energy requirements, such as increased glare and cooling loads. To ensure proper use, designers need design tools that model the dynamic nature of daylight and accurately predict performance with respect to a multitude of performance criteria, extending beyond comfort and energy to include aesthetics, cost, security, safety, etc.

Research and development efforts during the last twenty-five years have resulted in a number of computer-based tools, with varying degrees of modeling capabilities and prediction accuracy. Some of them, such as SuperLite [Modest 1982] and Lumen Micro [Baty 1996], are limited to daylighting computations with strict bounds on their modeling capabilities, while others, such as Radiance [Ward 1990] and Lightscape [Khodulev and Kopylov 1996], can model environments of arbitrary complexity and extend beyond daylighting and lighting computations to generating rendered images that are most helpful for the evaluation of lighting quality and aesthetics. Finally, some energy simulation tools, such as DOE-2 [Birdsall et al. 1990, Winkelmann et al. 1993] and Energy-10 [PSIC 1996], include simplified daylighting computations and integrate them with those on electric lighting, heating and cooling loads, HVAC performance, etc. Most of these tools, however, especially those with extended modeling capabilities and high degree of accuracy, such as DOE-2 and Radiance, are very expensive to use. In addition to extensive training, they require time-consuming preparation of input that describes the building and its context, and significant processing of the output to evaluate and analyze the predicted performance. In this paper, we present two software tools for the evaluation of daylighting strategies and technologies, from the initial, schematic phases of building design to the detailed specification of building components and systems.

The first tool is the Building Design Advisor (BDA), a PC-based software environment that facilitates the use of multiple simulation tools by automating the preparation of the required input

and integrating the output in graphic displays that support simultaneous evaluation of multiple design options with respect to multiple performance criteria [Papamichael et al. 1997]. The 1.0 version of BDA is linked to two simplified simulation tools, one for the prediction of daylight work-plane illuminance and glare index in rectangular spaces, called DELight, and the other for the prediction of monthly energy requirements by end use and energy source, called RESEGY. The second tool is the latest release of the Radiance program (version 3.1), which computes luminance and illuminance values for arbitrary space and fenestration configurations, as well as produces photo-accurate images of the modeled environment. This latest release of Radiance has several new features that enhance its usability for building design applications.

The Building Design Advisor (BDA)

The BDA is a computer program that supports the integrated use of multiple performance analysis and prediction tools, through a single, object-based representation of building components and systems. The BDA acts as a data manager and process controller, allowing building designers to benefit from the capabilities of multiple tools throughout the building design process. BDA has a simple Graphical User Interface that is based on two main elements, the Building Browser and the Decision Desktop.

The Browser (Figure 1) allows building designers to quickly navigate through the multitude of descriptive and performance parameters addressed by the analysis and visualization tools linked to BDA. Through the Browser the user can edit the values of input parameters and select any number of input and output parameters to display in the Desktop. The Desktop (Figure 2) allows building designers to compare multiple alternative design solutions with respect to multiple design considerations, as addressed by the analysis and visualization tools and databases linked to BDA. The Desktop supports a large variety of data types, including 2-D and 3-D distributions, images, sound and video.

BDA is linked to a Schematic Graphic Editor (Figure 3), that allows designers to quickly and easily specify basic building geometric parameters. Through a Default Value Selector, BDA automatically assigns "smart" default values to all non-geometric parameters required by the analysis tools from a Prototypical Values Database. In this way BDA supports the use of sophisticated tools from the initial, schematic phases of building design. All default values can be easily reviewed and changed through the Building Browser.

Solutions:	Views:	Whole Building Model	Update Desktop
SAN FRANCISCO		Parameter Name	Value Unit Type Source
LBHL Headquarters		heating_setpoint_temperature	70.00 degF Descriptive CEC TES
Dist_Sys_3		equipment_heat_to_hood_ratio	0.00 % Descriptive BDA
Heating_Plant_5		man_outside_per_person	5.00 cfm Descriptive ASHRAE Appl
Cooling_Plant_7		lighting_power_density	1.60 W/m^2 Descriptive ASHRAE 90.1
Default_Zone		air_volume_ratio	94.00 % Descriptive BDA
ground floor		miscellaneous_heat_to_hood_ratio	0.00 % Descriptive BDA
ground floor Plenum		light_heat_to_space_ratio	93.50 % Descriptive IESNA Hnbb
Conference		heating_setback_temperature	63.00 degF Descriptive CEC TES
Wall_18		workplane_height	3.00 ft Descriptive BDA
Ext_Wall_Seq_25		equipment_power_density	1.00 W/m^2 Descriptive CEC TES
Finish_27		ventilation_rate_per_person	20.00 cfm Descriptive ICBO UBC
Window_45		area_per_person	15.00 ft^2 Descriptive ICBO UBC
Frame		cooling_setpoint_temperature	78.00 degF Descriptive CEC TES
Glazing		miscellaneous_power_density	0.00 W/m^2 Descriptive BDA
Ground_Surface		cooling_setback_temperature	65.00 degF Descriptive CEC TES
Construction		occupant_orientation	0.00 degree Descriptive BDA
Wall_19		hot_water_use_per_person	0.00 gallons... Descriptive BDA
Wall_20		gross_area	960.00 ft^2 Geometry k_papamichael
Wall_21		grid_step	2.00 ft Geometry k_papamichael
Plenum_Boundary_22		volume	6640.00 ft^3 Geometry k_papamichael
Ceiling_23		floor_to_ceiling_height	9.00 ft Geometry k_papamichael
Floor_24		temporal_glare_index	C.V.BET... Performance DCM-ECM
Roof_49		spatial_workplane_illuminance	C.V.BET... Performance DCM-ECM
Hourly_Schedule		spatial_glare_index	C.V.BET... Performance DCM-ECM
Monthly_Schedule		monthly_electric_lighting_savings	C.V.BET... Performance DCM-ECM
Lighting_Control		temporal_workplane_illuminance	C.V.BET... Performance
Thermal_Activity		annual_electric_lighting_savings	C.V.BET... Performance
Visual_Activity			
Hourly_Schedule			

Figure 1. The Building Browser allows BDA users to navigate through the building model to review and edit the values of objects and parameters. Moreover, it allows them to select which parameters they want displayed in the Decision Desktop for decision making.

BDA is implemented as a Windows®-based application for personal computers. The initial version is scheduled for release in 1998, and includes links to DELight, RESEGY, and a Web-based multimedia Case Studies Database. Future versions of BDA will be linked to additional analysis tools, such as the DOE-2, Radiance and COMIS [Feustel 1992], as well as to cost estimating and environmental impact modules, building rating systems, CAD software and electronic product catalogs.

The DELight software

The DELight daylighting analysis engine currently linked to BDA is based on the DOE-2 daylighting algorithms, which operate in three key stages [Winkelmann 1983, Winkelmann and Selkowitz 1985]. A preprocessor calculates sets of daylight factor and glare index values for a grid of sun positions, assuming standardized clear and overcast sky conditions. An hourly calculation is then performed to determine interior daylight illuminance levels and glare index values, using outdoor daylight illuminance values and interpolating on the predetermined values to account for the exact position of the sun. Lastly, either stepped or continuous dimming control of the electric lighting system is simulated to predict potential reductions in electric lighting loads and associated savings.

The DELight implementation of the DOE-2 daylighting algorithms includes some key modifications. The number of reference points within a zone for which lighting level and glare index calculations can be performed has been increased to enable evaluation of the spatial distribution of daylight in a space (Figure 4, top image). As a computational trade-off DELight cannot individually control window shading on an hourly basis as is possible with DOE-2. In

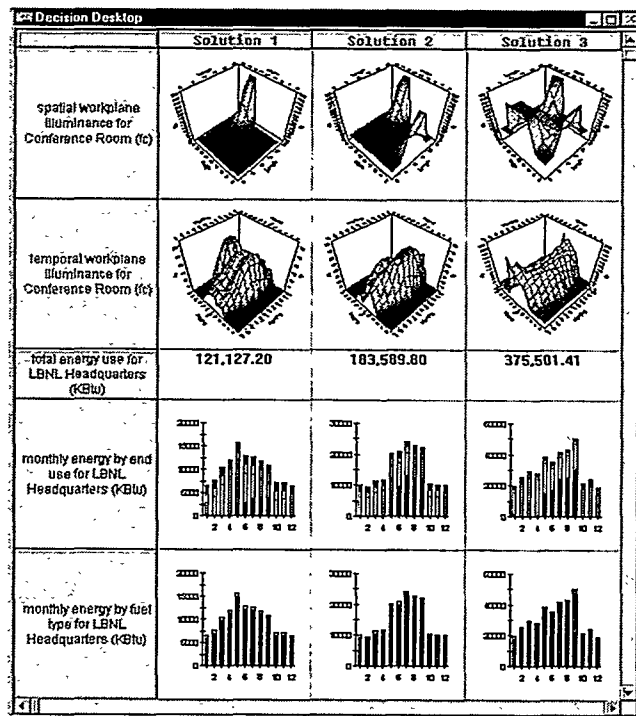


Figure 2. The Decision Desktop is a spreadsheet that allows BDA users to compare multiple solutions (columns) with respect to multiple criteria (rows), which may be input or output parameters of any of the tools linked to BDA.

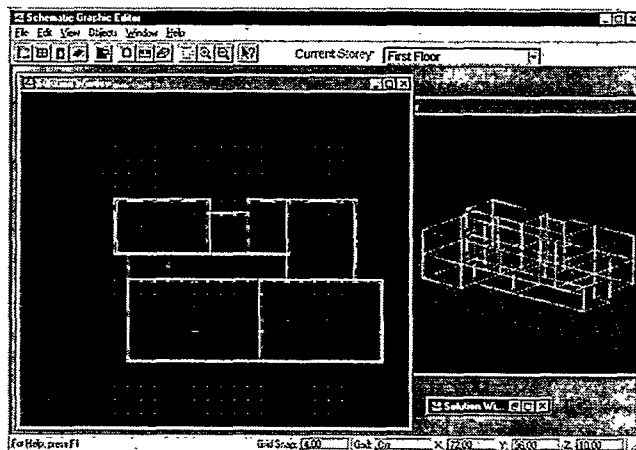


Figure 3. The Schematic Graphic Editor is a separate application that supports schematic design by allowing users to draw and manipulate building objects, such as spaces and windows, while continuously communicating with BDA for the development of a complete data model.

addition to an hourly simulation using measured weather data, DELight can perform a “snapshot” calculation for a single sun position, or hourly calculations for one day of each month, using theoretical sky conditions (Figure 4, bottom image).

DELight is written in highly portable ANSI C and modularized to allow either standalone execution or relatively easy integration with other software modules. In addition to BDA, versions of the DELight engine have been successfully linked with the AEDOT prototype [Pohl et al. 1992] and ENERGY-10 [PSIC 1996, Hitchcock 1995].

The RESEGY software

The RESEGY thermal and energy simulation engine is a fast, robust, whole-building energy simulation program that can be easily linked to other software tools such as BDA. RESEGY was originally designed and written in 1990 as an embedded thermal simulation engine for RESEM, a retrofit savings verification tool developed for the evaluation of federally financed energy conservation retrofits in institutional buildings [Carroll et al. 1989]. In this context, RESEGY had to be comprehensive enough in its energy modeling to explicitly reflect the influence of a wide range of design, operation, weather parameters, and retrofit strategies encountered in the target building types.

The RESEGY energy analysis approach has its conceptual foundations in the ASHRAE modified bin method [Knebel 1984], altered to use monthly bins and to simulate complete HVAC systems and plant equipment

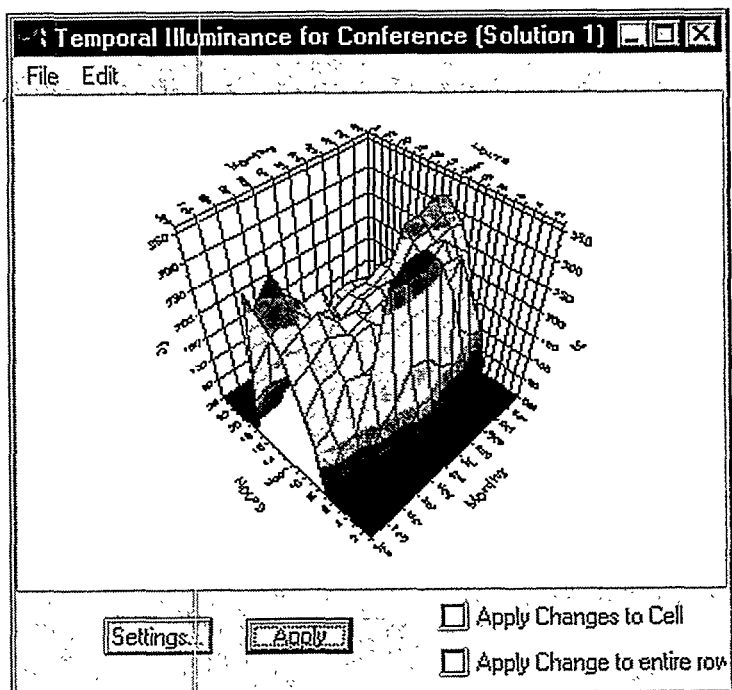
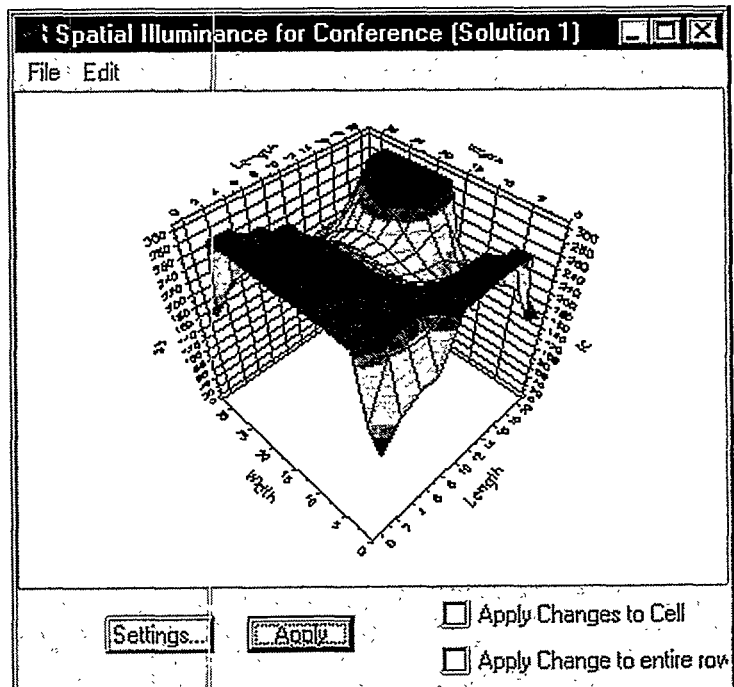


Figure 4. Spatial (top) and temporal (bottom) distributions of daylight work plane illuminance computed by DELight and automatically displayed by BDA.

performance at each bin condition. To the degree possible, the energy estimation model developed for RESEGY was based on existing, public domain methods and algorithms [ACEC 1991, York and Cappiello 1981]. This minimized development and validation efforts and provided a certain degree of credibility as well. RESEGY models major building envelope components, zones, internal loads, operational parameters (e.g., thermostats and use schedules), several generic HVAC systems that can be customized to represent many actual system designs, and all major plant equipment types. Automatic HVAC fan system and plant equipment sizing capabilities are also provided. Complex multi-zone buildings can be described and simulated in a straightforward way. Simulated building energy consumption results are broken down into a matrix of components by month, fuel type, and end use (Figure 5). RESEGY results have been compared to DOE-2 simulations in several unpublished studies with generally good agreement.

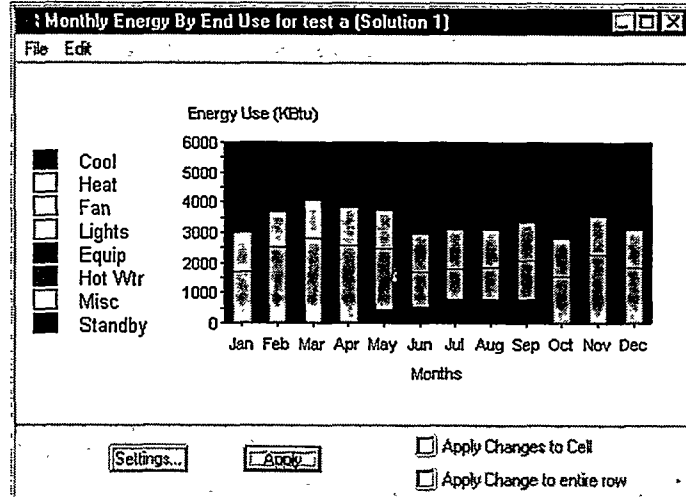


Figure 5. Monthly totals for energy requirements by end use computed by RESEGY and automatically displayed by BDA.

RESEGY uses a separate weather data processor that uses hourly NOAA weather data for input (both actual-year data and typical years in TRY or TMY formats) and provides as output the bin data necessary for RESEGY computations. The output of the weather processor also contains summary design condition information. At this time a weather library has been created for about 220 U.S. cities, with both average (TMY) and actual weather years from 1981 to 1990.

The Radiance 3.1 software

The development of Radiance began in 1988 in an effort to accurately predict the distribution of light in architectural spaces [Ward 1994]. The latest release, version 3.1, represents the ninth official revision to the software, incorporating ten years of development, refinement, and validation. Radiance uses a combination of ray tracing and radiosity algorithms to determine luminance or illuminance values, which are then further processed to produce photometrically accurate renderings. Radiance models environments based on five primary surface types (polygon, sphere, cylinder, cone, and ring) which can be combined to represent the geometry of most real world objects. The material properties of surfaces can be either self-luminous (light for unlimited range of effect and glow for a defined radius of effect) or non-luminous (plastic, metal, dielectric and translucent materials). All materials can be modified by *patterns* that change the material reflectance and color, or by *textures* that change the surface normal to simulate bumps or large-scale roughness.

Radiance has been developed under the UNIX operating system as a collection of several programs. The program RAD helps the user by providing a set of input control variables for calculation accuracy, desired image quality, geometric detail, and light variability. A single

invocation of the RAD program handles all of the sub-command calls and input parameters to achieve either quick thumbnails or presentation quality renderings. Available script files automate various tasks, such as the creation of physically accurate light sources, the calculation and display of polar plots that indicate glare problems, the calculation of illuminance values and daylight factors at the work-plane, and the creation of false-color images for visualizing various lighting quality metrics.

RADIANCE 3.1 includes two major enhancements: the automatic generation of walk-through animations, handled through the program RANIMATE [Ward and Shakespeare 1998], and the application of appropriate human-sensitivity exposure adjustments for images of high dynamic luminous range, handled by the program PCOND [Ward et al. 1997]. Together these features enhance the designer's ability to evaluate and understand the dynamic nature of daylight in buildings.

The RANIMATE program

RANIMATE extends the framework of the still-frame rendering control program (RAD) into the realm of animation computations suitable for multi-processing by multiple networked computers. The user specifies sequence control and hardware resource parameters, as well as accuracy and exposure controls using text files, and executes a single command that coordinates the optimized calculation of the defined animation. Prior to RANIMATE, the creation of animations was a painstaking process using custom-crafted script files, which would quickly exhaust system resources, e.g., hard disk space for storing temporary files.

RANIMATE was used to control the computation of an animation sequence through the San Francisco International Airport, Air Traffic Control Tower. An MPEG version of this animation can be viewed at <http://radsite.lbl.gov/airport/sfoatct5.mpg>. The frame-rendering rate was approximately 20 minutes per frame on a 100Mhz Pentium-class machine.

The PCOND program

PCOND relieves the user of the arduous task of previous versions of Radiance to determine the appropriate light exposure setting for the final renderings. An inappropriately defined exposure can give false impressions with respect to the available light levels, glare or veiling reflection problems, thus easily misleading inexperienced users to inaccurate conclusions. While PCOND has yet to be fully validated with human subject studies, results are intuitively correct and sometimes astonishingly convincing, when previous versions left high luminance and out-of-gamut parts of the displayed image either too bright or too dark.

PCOND was used to produce a series of simulated images of a critical view from the interior of the SFO Air Traffic Control Tower as they might appear under different human adaptation levels. Three of these images are shown in Figure 6. The left image is exposed considering the influence of the circum-solar region while the middle image is taking into consideration the adaptation of the eye when focused on VDT and paper tasks. The right image shows the same view exposed for VDT and paper tasks without the adjustments of the PCOND program. Notice how the exterior details are lost due to this part of the image being beyond the gamut of the limited dynamic range of the display device (reflective paper or RGB monitor).



Figure 6. The same view is processed with PCOND to account for the influence of the circum-solar region (left) and for the adaptation of the eye when focusing on the VDT and paper tasks (middle). The right image shows the view without PCOND processing.

Plans for the future

Our plans for the future include the development of links between a PC version of RADIANCE and BDA. With BDA also being linked to the DOE-2 building energy simulation program, as well as to DELight and RESEGy, we expect to integrate the use of simplified and sophisticated tools to address daylighting from the early, schematic phases of building design through the detailed specifications of building components and systems. Current work on the DELight engine includes the ability to model complex fenestration systems characterized by bi-directional transmittance data, and the incorporation of radiosity algorithms for the calculation of internally inter-reflected light. An important objective of this work is to maintain relatively fast execution times. Future development of RADIANCE includes the creation of improved user interfaces and on-line support, as well as a real-time, interactive, virtual-reality display, through links to a supercomputer. Although supercomputer capabilities will not be widely available to average users, the pupil-tracking fovea-weighted display techniques and the underlying parallel processing approaches will be useful to speed calculations on the emerging generation of high powered, networked desktop computers.

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