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INTEGRATED SIMULATION ENVIRONMENT FOR LIGHTING DESIGN

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ABSTRACT: Lighting design involves the consideration of multiple performance criteria, from the earliest stages of conceptual design, through various stages of controls and operation in a project's life cycle. These criteria include *a)* the quantitative analysis of illuminance and luminance distribution due to daylighting and electric lighting, *b)* qualitative analysis of the lighting design with photometrically accurate renderings of the designed environment, *c)* analysis of energy implications of daylighting and electric lighting design and operation, and *d)* analysis of control strategies and sensor placement for maximizing energy savings from lighting control while providing visual comfort.

In this paper we describe the development of an integrated decision-making environment that brings together several different tools, and provides the data management and process control required for a multi-criterion support of the design and operation of daylighting and electric lighting systems. The result is a powerful design and decision-making environment to meet the diverse and evolving needs of lighting designers and operators.

INTRODUCTION

All design involves predicting and evaluating multiple performance criteria, and lighting design is no exception. Early generations of computer tools for predicting and evaluating lighting performance were largely based on simplified algorithms that had been developed for manual calculation of light levels (Hopkinson, 1966; IES, 1993). These tools were devised to help a lighting designer meet quantitative criteria, such as average illuminance on the work plane. Today, advanced lighting simulation tools provide photometrically accurate renderings of a lighting environment (Ward and Shakespeare, 1998; Sillion and Peuch, 1994), offering designers both qualitative and quantitative information about their designs. However, these computationally intensive tools are not designed for quick parametric and temporal analyses. Another limitation is that most lighting tools do not permit analysis of the energy implications of daylighting and electric lighting designs and their operation. On the other hand, some energy analysis programs (Birdsall et al., 1990) allow consideration of energy savings from daylight-responsive electric design, though their algorithms for predicting lighting performance are simplified.

In short, a designer who wants to use multiple criteria to evaluate a lighting design must use several tools, each of which only partially addresses his/her prediction and evaluation needs. One difficulty with

this process results from the necessity of providing input data for each of these tools individually and then collecting and manually integrating the output. In many cases, manual integration of output may not be even possible; the output of one tool may be the input of another, and the output may require manipulation before another tool can use it as input.

To address these difficulties, a lighting design decision-making environment is needed that integrates the various aspects of lighting performance and provides the data management and process control required for a multi-criterion evaluation of the design and operation of daylighting and electric lighting systems. This paper describes such an environment. The next section outlines the architecture of a computational environment that enables integration of different tools for predicting and evaluating multiple performance criteria. We then describe how this integration is achieved specifically for lighting and daylighting design.

SIMULATION ENVIRONMENT

An environment that supports the use of several different simulation tools must support the different building representations required by each tool. In addition, it has to accommodate the incorporation of new tools as needed, so its underlying data schema must be flexible and expandable. A process control mechanism is also needed to manage the activation of

tools and the data exchange among them. Further, to support decision-making, the environment should provide the means for performance evaluation as well as performance prediction. These requirements are addressed through the software architecture and graphical user interface of the Building Design Advisor (BDA), an integrated simulation environment that we developed for this purpose (Papamichael et al., 2000; Papamichael et al., 1997).

Software architecture

BDA uses an object-oriented representation of the building in the form of two data schemata -- the *Meta Data Schema* and the *Building Data Schema*. The Meta Data Schema models the building at a low level of abstraction using "building objects" that are related through "relation objects" and characterized by "parameter objects" (Figure 1). The Building Data Schema builds on the Meta Data Schema, defining specific building objects (e.g. "spaces," "walls," "windows"), relation objects (e.g. "composed_of / part_of," "has / owned_by"), and parameter objects (e.g. "U-value," "visible transmittance," "area"). New objects can be added to the Building Data Schema in the same way data are added to a database, so the object model can be expanded in a flexible and modular manner through the creation of new building objects, as well as new relation objects and parameter objects for new and existing building objects.

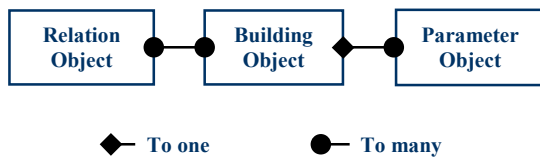


Figure 1: Building objects, Parameter objects, and Relation objects in the Meta Data Schema.

The environment also maintains databases of alternative options for every building object defined in the Building Data Schema. Designers can refine designs by selecting building components and systems (e.g., luminaires, glazings) from these databases of options just as they would select products from the manufacturers' inventories. Designers can also generate and maintain multiple solutions for a single project to compare and contrast different options (Figure 2).

Processes and tools are also defined as objects in the Meta Data Schema. These "process objects" are related to "parameter objects" and "building objects" through input and output relations (Figure 3). This allows a process control mechanism to check for interdependencies between parameters and activate processes to supply values for the performance

parameters. The designer selects the performance parameters to be computed and this triggers a chain of process activations.

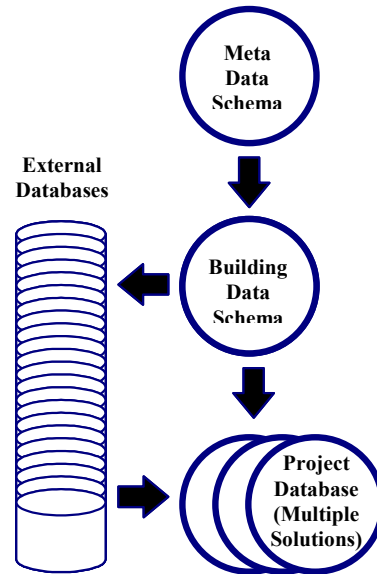


Figure 2: The relationships among the data meta-schema, the building data schema, the project database, and the external databases.

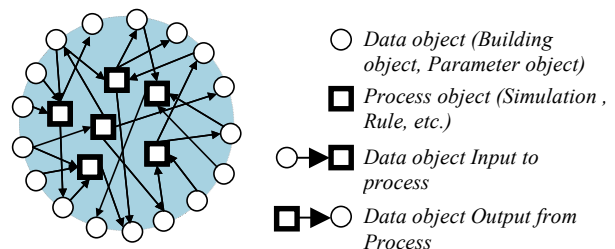


Figure 3: Processes modeled as links among data.

User Interface

BDA has three main user interface components: a Schematic Graphic Editor (SGE), a Building Browser (BB), and a Decision Desktop (DD) (Figure 4).

The SGE is a CAD interface to the environment but, unlike traditional CAD packages, it allows the user to draw specific building components, such as "spaces," "windows," and "luminaires," rather than lines that represent these objects. Objects drawn in the SGE hold semantic information about themselves and their relationships; this information is structured in a hierarchical form as a project tree in the Building Browser. The Building Browser allows the user to navigate the building model and edit all values for

building objects and parameters. The user can access the databases of options from the browser and select luminaires, glazings, etc., change parameter values, and select parameters for computation. Computation results are displayed in the Decision Desktop, which is structured as a matrix of cells to facilitate comparison of multiple design solutions in relation to multiple parameters for ease of performance evaluation. The matrix rows correspond to the parameters selected by the user in the Building Browser; the columns correspond to alternative design solutions that have been defined by the user. The performance parameter information displayed in these cells may be in the form of numbers, 2-D and 3-D graphs, images, or even multi-media files.

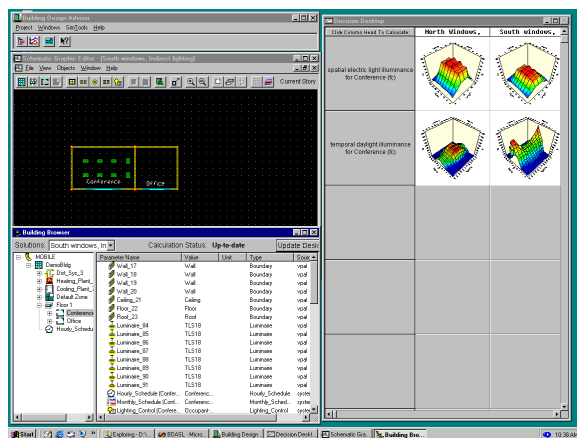


Figure 4: The main User Interface elements of the BDA software.

Linked tools

BDA brings together a) DELight, a simplified daylight calculation tool (Hitchcock, 1995), b) ECM, a newly developed simplified electric lighting calculation tool, and c) DOE2.1E, a popular and time-tested energy analysis tool (Birdsall et al., 1990). Links with Radiance, a complex, ray-tracing based daylighting and electric lighting calculation and rendering tool (Ward and Shakespeare, 1998), are currently being developed.

The DELight computational engine is based on the DOE2 daylighting algorithms. It extends these algorithms so that illuminance and glare values may be calculated at a user-defined grid of points within a zone. Daylight Factors are computed for standard clear and overcast sky conditions, and for a series of 20 solar altitude and azimuth values that cover the annual range of sun positions. Then hourly values for illuminance are computed by interpolation between these values. The window geometry, glazing transmittance, surface reflectances, and room

geometry are taken into account in the calculations. The geometry is limited to rectangular rooms.

The ECM combines the simplicity of the IESNA Zonal Cavity Method (IES, 1993) with a more analytical approach for calculating the direct component of illuminance. The direct component of illuminance is calculated at each of the grid points on the workplane using the luminaire's candlepower distribution and the geometric relationship between the luminaire and the grid point. The indirect component of illuminance is computed using a modified version of the IESNA Zonal Cavity Method. As in DELight, the geometry is limited to rectangular rooms.

Radiance calculates light levels for, and renders images of the lighting design. It uses a hybrid approach of Monte Carlo and deterministic ray tracing to simulate the light transfer between surfaces (<http://radsite.lbl.gov/radiance/framew.html>). It can perform simulations for complex geometries and reflectance/transmittance functions.

DOE2.1E predicts, among other things, the hourly energy use for a building. It requires hourly weather information along with a description of the building and its HVAC equipment and occupancy patterns. Among the factors that it takes into account are weather and solar conditions, electric lighting loads, window geometry, glazing properties, and shading.

BRINGING IT ALL TOGETHER

The simulation environment described above, together with the tools linked to it, allows for quantitative and qualitative analyses of the lighting design. It also allows for an energy analysis of the lighting design, as well as analyses of various control strategies.

Quantitative analysis

The SGE is used to draw spaces and place windows, overhangs, and/or vertical fins. Luminaires can be placed in the space by simply clicking on the desired position, and can subsequently be rotated as needed. Spaces, windows, and luminaires may be moved or deleted. If a space is moved, the windows and luminaires move with it. Figure 5 shows the SGE with spaces drawn. Figure 6 shows a space with windows, luminaires, and sensor points added. The user can select any object to view its properties, and different options for luminaire types and glazing types may be selected as shown in Figure 7.

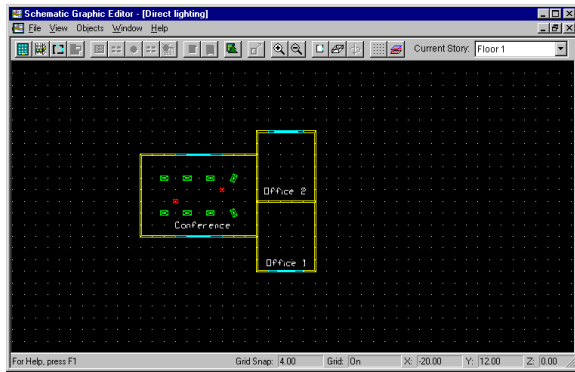


Figure 5: The SGE with spaces drawn into it.

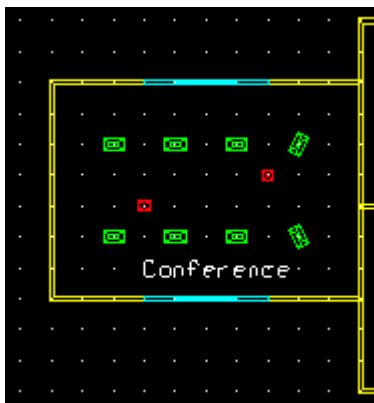


Figure 6: A space with luminaires, windows and sensor points.

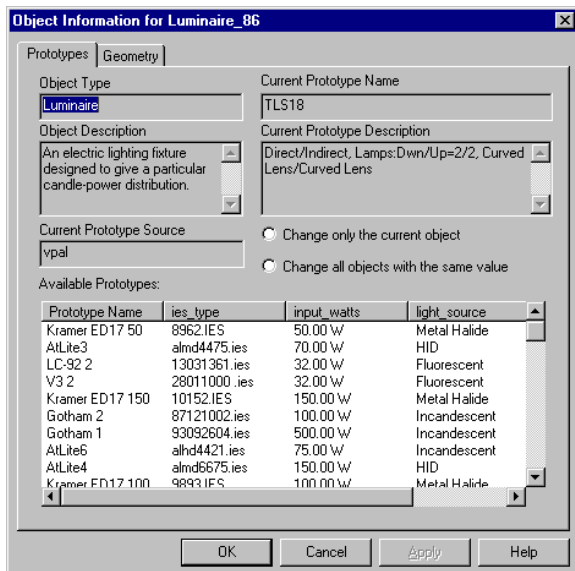


Figure 7: Selection of a luminaire prototype from a database of luminaire options.

The user can select various performance parameters to be computed, e.g., spatial illuminance from daylight, temporal illuminance from daylight, spatial illuminance from electric lighting, and spatial or temporal glare values. DELight and ECM are activated accordingly. Figure 8 shows results for spatial electric lighting illuminance and temporal daylight illuminance for two different solutions displayed in the Decision Desktop.

The results from DELight and ECM are available only for rectangular rooms since the algorithms that these tools use cannot model more complex spaces. Radiance can provide illuminance and luminance values for spaces with arbitrary geometric complexity.

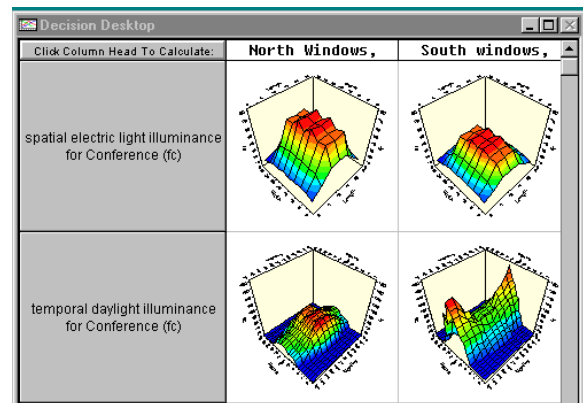


Figure 8: Performance values displayed in the Decision Desktop for comparative evaluation.

Qualitative analysis¹

If the designer chooses to view the lighting design as an image, Radiance is activated. The geometry defined by the user in the SGE is written to Radiance input files. Input files for material, luminaire, and glazing properties are also written. The designers do not have to manually assign semantic properties to objects. They can simply choose from a selection of finishes, luminaires, and glazings. No special development effort is needed to facilitate this process because the simulation environment already has the infrastructure in place for selecting from libraries of options. The databases of options are simply extended to include semantic information required by Radiance for materials, luminaires, and glazings.

The camera can be graphically dropped and positioned within the space in much the same way

¹ At the time of writing this paper, the Radiance link is not included in the public release of the BDA software.

that luminaires are placed and rotated. Figure 9 shows a Radiance image generated from within BDA.



Figure 9: Radiance image generated through BDA.

Energy analysis

DOE2.1E, the energy analysis tool linked to BDA, allows the consideration of electric lighting and daylighting in its calculations of energy use, cooling loads, and heating loads. However, some simplifying assumptions are made by DOE2.1E in its simulation of daylighting and electric lighting. The electric lighting design is accounted for as a single number, the lighting power density, which the user has to compute and provide. Further, the assumption is made that the electric lighting design at full power exactly meets the desired illuminance level at a point of interest. When the user is given the freedom to design the electric lighting, by selecting and placing luminaires in the space, this might not be the case. The designer may "over-design" or "under-design" relative to the illuminance requirements. The designer should be notified of this but if they choose to keep the design, the energy use and electric lighting savings due to dimming should reflect the actual design.

In the BDA the power density is computed as the designer inserts, deletes or modifies the luminaires. When the designer requests the value of an energy-related parameter that needs to be calculated by DOE2.1E, this constantly updated value is supplied to DOE2.1E. Further, BDA takes advantage of DOE2.1E's capability to accept user-defined functions to locally modify its algorithms. The software uses a function that modifies the hourly calculations by DOE2.1E for computing the fractional lighting power input for daylight-responsive dimming. The dimming curve is modified to reflect the actual illuminance provided by the electric lights at full power on a sensor point, instead of relying on the assumption that the target illuminance is exactly met at full power. The value of the illuminance from electric lighting at the sensor point is provided by ECM. Radiance results for

electric lighting are expected to be more accurate than the results computed by ECM and can easily be used instead, though the calculation would take more time.

The link between BDA, ECM and DOE2.1E is shown in a diagram in Figure 10. Figure 11 shows the difference in the electric lighting savings with continuous dimming for two different designs. The spatial illuminance due to electric lighting for the two designs is also displayed. Figure 12 shows the difference in the energy consumption of the project due to two different lighting schemes. This difference includes the impact of the electric lighting design on the heating and cooling loads of the building.

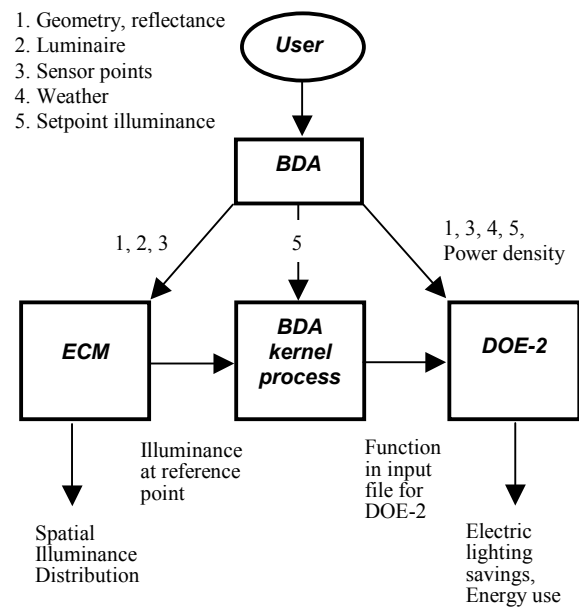


Figure 10: Exchange of data between BDA, ECM and DOE2.1E.

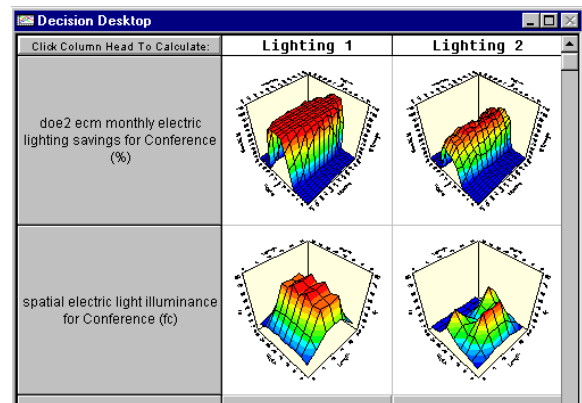


Figure 11: Difference in electric lighting savings with dimming for two different designs.

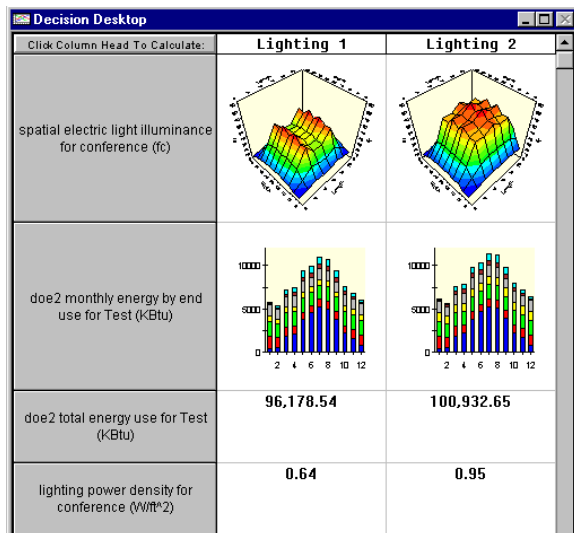


Figure 12: Difference in energy consumption due to two different electric lighting designs.

The designer can double-click on any of these graphs to open them in a larger window showing greater details. Figure 13 shows the details of an energy consumption graph.

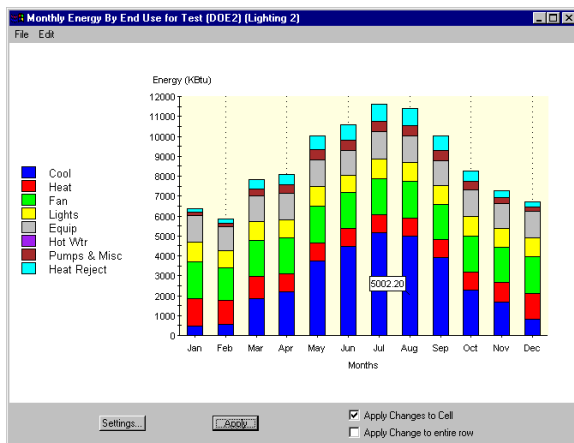


Figure 13: Details of the "doe2 monthly energy by end use" graph.

As previously mentioned, DOE2.1E's daylighting algorithms use simplifying assumptions about the sky conditions and space geometry. Radiance, in contrast, uses physically based algorithms for calculating daylighting. Radiance uses more accurate sky luminance models than DOE2.1E and is not limited to modeling rectangular rooms. We are therefore planning to use Radiance results to replace DOE2.1E calculations for daylight, hopefully achieving more accurate results for energy savings due to daylight. We plan to follow a concept that is similar to the one that was implemented for using the electric lighting results from ECM. In this case, we will use Radiance

to calculate the daylight factors for the series of 20 solar altitude and azimuth values covering the annual range of sun positions that is required by the DOE2.1E daylighting algorithms. A function can then be defined to replace the DOE2.1E calculated values for these positions with the values calculated by Radiance.

Lighting controls

The designer may want to model the lighting control system in greater detail than simply selecting the type of lighting control strategies and assigning zonal fractions of a space to each strategy. They should be able to select control strategies, place any number of sensor points, and create lighting zones by creating links among the various luminaires, sensor points and control strategies.

Each space may have zero or more luminaires, and zero or more sensor points. If we consider "no controls" as a control strategy, then each space can have one or more control strategies corresponding with one or more zones within the space. Each sensor point may control zero or more luminaires. Each sensor point may also be associated with a particular control system, e.g. a continuous dimming or stepped dimming system. Or it may not be associated with any controls at all and be used just for recording light levels. Consequently, there is a network of associations here that the designer should be able to define (Figure 14).

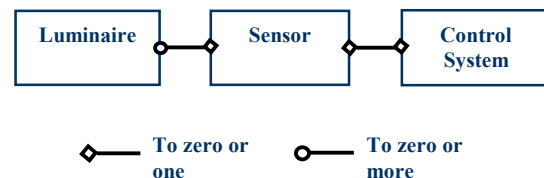


Figure 14: The relations between the luminaires, sensors, and the control system.

Fortunately, the software architecture of BDA is set up to allow the user to make these associations easily using "relation objects", in a manner that can transparently be observed and controlled. Figure 15 shows the user interface for assigning luminaires to be controlled by any particular sensor point. The sensor points can be graphically placed, moved around, and deleted in the SGE. Figure 16 shows the user interface for linking a control strategy with a sensor point.

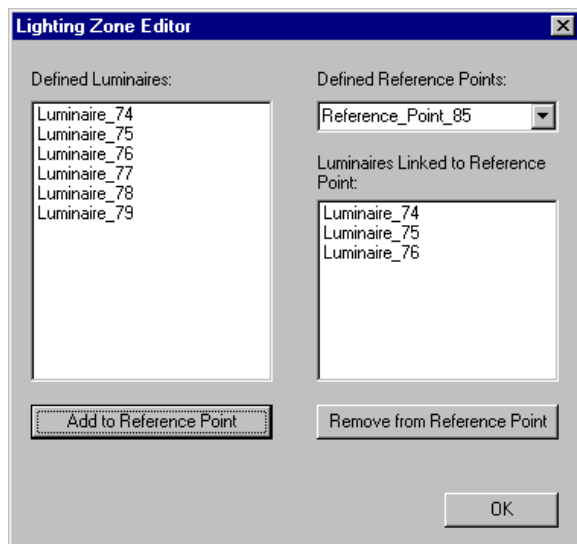


Figure 15: Defining relations between a sensor point and the luminaires it controls.

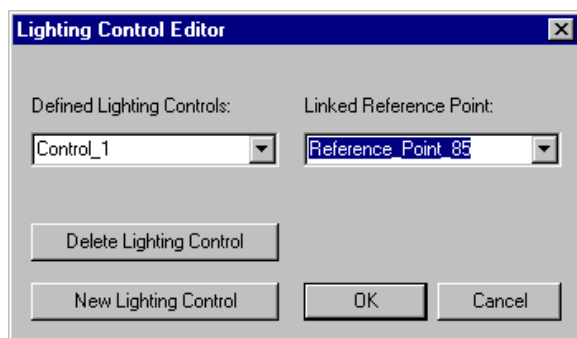


Figure 16: Defining relations between a sensor point and the lighting control system.

The semantic information about the control strategies, the luminaires, and the sensor points is displayed, and can be modified in the Building Browser. The associations made by the user between the various components of the control system are immediately reflected in the project tree of the Building Browser (Figure 17). For DOE2.1E, which uses zonal fractions, the information is translated to zonal fractions. However, the information can be used without modification by Radiance to visualize various dimming scenarios.

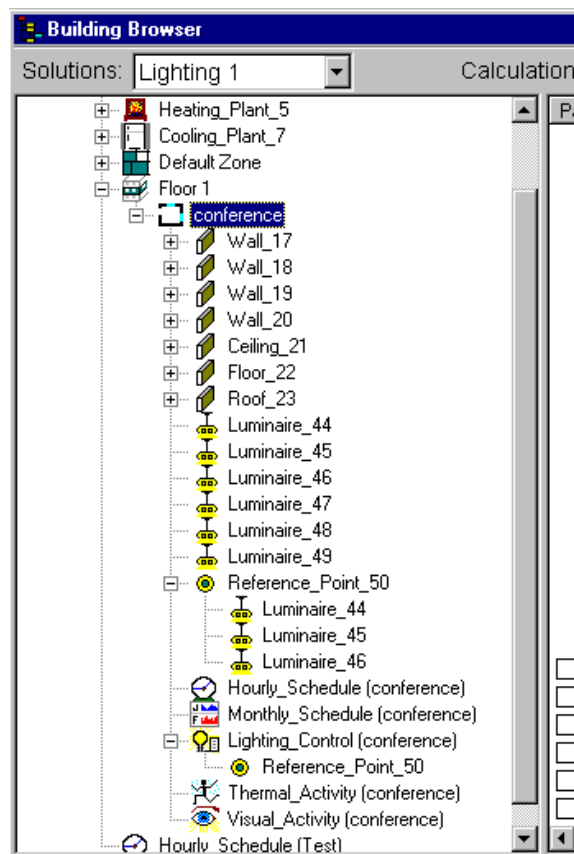


Figure 17: The associations made by the user among the lighting control, the reference points, and the luminaires are reflected in the Building Browser.

CONCLUSIONS

In this paper we have described an integrated lighting simulation environment that enables the user to consider multiple performance criteria for the design and operation of daylighting and electric lighting systems. The architecture of this simulation environment allows us to bring together a number of tools that address different aspects of the lighting system. The output of one tool is easily used as input to another, either directly, or after appropriate manipulation to ensure compatibility, which makes the whole integrated environment more than the sum of its parts. The combination of simplified as well as sophisticated tools for daylighting, electric lighting and energy, allows prediction and evaluation of performance at various levels of accuracy, as needed, in different stages of the design process.

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