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Advancing Lighting and Daylighting Simulation: The Transition from Analysis to Design Aid Tools

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ABSTRACT

This paper explores three significant software development requirements for making the transition from standalone lighting simulation/analysis tools to simulation-based design aid tools. These requirements include specialized lighting simulation engines, facilitated methods for creating detailed simulatable building descriptions, and automated techniques for providing lighting design guidance. Initial computer implementations meant to address each of these requirements are discussed to further elaborate these requirements and to illustrate work-in-progress toward fulfilling them.

INTRODUCTION

The art of lighting and daylighting performance analysis for buildings has become science. However, considerable work is left in the effort to transform this available science into building design, construction and operation practice. Well developed algorithms exist for simulating the performance of buildings. These algorithms have generally been implemented as standalone performance evaluation tools which in turn have been used to develop simplified design guidelines. However, recent effort has shifted to making the transition from pure simulation/evaluation tools to simulation based design aid tools. This transition has already been made in industries such as semiconductor design and manufacturing, but has yet to move beyond the prototype stage for building design, construction and operation.

This paper is an exploration of the requirements for developing simulation based design aid tools that integrate lighting and day lighting analysis into the building life-cycle process. These requirements include robust and fast simulation engines that are easily integrated into whole building thermal simulation, easy generation of product-based reference-case building descriptions, and automatic application of lighting and daylighting design guidelines.

The following sections address each of these requirements in more detail. Some existing lighting and daylighting analysis algorithms and tools, SUPERLITE (LBL, 1994), DOE-2 (Winkelmann, 1983; Winkelmann and Selkowitz, 1985), and the author's evolving analysis engine DElight, are reviewed for their application to the development of design aid tools. Methods for facilitating the generation of simulatable reference-case building descriptions based on common building practices are discussed. The issues of easy access to, and application of, adaptable design guidance related to improving the lighting performance of the reference building are also addressed. Techniques implemented in two computer tools, RESEM (Carroll, et al. 1989) and ENERGY-10 (NREL, 1995), are used to illustrate these processes.

LIGHTING SIMULATION ENGINES

Simulation based design aid tools that address lighting issues require a lighting analysis engine capable of determining interior lighting levels and some measure of lighting comfort. These building performance characteristics must be calculated, using actual weather data as input, so that both spatial distribution within a building interior and temporal variations during an individual day and throughout an entire year, can be assessed. The engine must be fast enough to allow rapid experimentation with various lighting design parameters. The engine must also be robust enough to accurately account for variations in design parameters such as room and building site configuration, interior and exterior surface reflectance, complex fenestration system types, and commercial electric lighting system types. The engine itself, or its simulation results, must be easily integrated with whole building analysis to account for design interdependencies between daylighting, electric lighting and thermal performance.

There are numerous simulation tools currently available for lighting analysis. This section focuses on three public domain programs developed at the Lawrence Berkeley Laboratory that perform lighting analysis in differing ways for different purposes. The characteristics of each of these programs are reviewed here for assessing their potential to fulfill the identified requirements for a design aid tool.

SUPERLITE

SUPERLITE 2.0 (LBL, 1994) is a DOS based program that performs daylighting and electric lighting analysis in complex building spaces. SUPERLITE is a radiosity based analysis engine that accounts for direct, externally reflected and internally reflected light in its calculation of interior illuminance levels. The program calculates lighting levels on all interior surfaces (luminance) as well as on planes that can be arbitrarily positioned to represent work surfaces or other locations of interest to the user (illuminance).

SUPERLITE fulfills several of the requirements for a design aid tool engine. The radiosity approach accurately accounts for variations in design parameters such as room and building site configuration, interior and exterior surface reflectance (assumed perfectly diffuse), and commercial electric lighting system types (input using candlepower distribution data). Version 3.0 will address the issue of complex fenestration system types such as geometrically complex shading devices. The program calculates spatial lighting distribution and can be controlled to analyze one day a month for a full year.

However, SUPERLITE falls short of fulfilling other requirements. There is no visual comfort calculation. Calculation results are generally based on theoretically calculated daylight availability data for standard sky conditions. The calculation time for a simple space with one window, for a single sky condition, is approximately 10 seconds on a 66 MHz 486 machine. This execution time would be prohibitive when expanded to include multiple lighting zones with numerous windows, for a complete annual analysis. Also, although SUPERLITE is capable of calculating light levels due to electric lights, there is no integration between interior daylight levels and a corresponding electric lighting system dimming response. Lastly, it requires an additional software link such as DayLink (LBL, 1989) or SuperLink (Szerman, 1994), and manual data file transfers, to link SUPERLITE to a whole building thermal analysis tool.

DOE-2

DOE-2 is an energy use analysis program that calculates building sensible and latent loads, and simulates HVAC systems and plant behavior for a whole building thermal analysis. The program also includes an economic analysis of the cost of energy sources. DOE-2 includes a daylighting analysis calculation (Winkelmann, 1983; Winkelmann and Selkowitz, 1985) that has three key stages. A preprocessor calculates a set of “daylight factors” for a grid of standardized sun positions and sky conditions (clear and overcast). An hourly daylight and glare calculation is then performed to determine interior illuminance at a defined reference point within a zone. Lastly, either stepped or continuous dimming control of the electrical lighting system is simulated to calculate both electric lighting savings and the thermal impact of reduced lighting loads.

This is a highly effective approach to integrating dynamic lighting level and visual comfort analysis into a whole building thermal analysis. The only compromises made in regard to the requirements for a design aid tool are the limitations of spatial lighting distribution simulation (a maximum of two points in each zone), the simplified modeling of the electric lighting system (using only installed lighting density and linear dimming controls), and a less accurate split-flux algorithm for calculating interior reflected light. Each of these compromises was dictated by the need to reduce execution time in an hourly annual simulation.

DELIGHT

A lighting and daylighting analysis engine under development by the author builds on the DOE-2 and SUPERLITE lighting algorithms in an attempt to tailor the engine to the requirements of a design aid tool. The DElight engine is currently based on the

DOE-2 lighting algorithms with two key modifications. The number of reference points within a zone, for which lighting level and glare index calculations can be performed, has been changed from a maximum of two to an easily modified number (generally 100 in existing applications). This modification addresses the issue of evaluating the spatial distribution of light in a space. Second, the engine has been entirely re-written in highly portable ANSI C, and modularized to allow either standalone execution or relatively easy integration with other software modules. Versions of the engine have, to date, been successfully linked with three ongoing software development projects: the AEDOT- 1 prototype in a UNIX environment, and BDA the Building Design Advisor (Papamichael and Selkowitz, 1991) and ENERGY-10 (NREL, 1995) in the Windows 3.1 environment.

Current and future work on the DElight engine include the addition of electric lighting system simulation based on product level luminaire photometric data, the ability to simulate complex fenestration systems, and the incorporation of radiosity algorithms for the calculation of interreflected light. An important effort in this work will also be to maintain relatively fast execution times. Each of these enhancements is meant to improve the DElight engine for application in the development of lighting design aid tools by using the strengths of the DOE-2 and SUPERLITE approaches while alleviating their compromises.

BUILDING DESCRIPTION GENERATION

To be directly applicable to building design and specification, design aid tools must operate on a description of a building that accurately matches the actual building to be constructed and operated. While this may seem an obvious point to design practitioners, most building simulation work tends to be applied to generic building descriptions in an effort to develop simplified design rules-of-thumb. A design aid tool, on the other hand, must work with a detailed building description that includes commercially available building components, correctly arranged within the detailed geometry of the building.

An example of this distinction is evident in fenestration design. If a building is to be constructed using commercially available prefabricated window and frame elements, the simulatable building description cannot contain simple strip windows with area and glazing characteristics defined using continuous variables of square feet, solar heat gain coefficient and visible transmittance. Instead, the window characteristics must be selected from a discrete set of values that match available products. Furthermore, the windows must be accurately positioned in their host walls, geometrically accounting for window frames.

Developing such a detailed and accurate description of the building can be a time consuming and error prone process. This process must be facilitated by the design aid tool so that a complete simulatable building description can be easily created by the user. This process must also be user controllable so that the resulting description accurately reflects the building program (i.e., site, floor area and functional specifications) and mimics common building practices, rather than producing a simplified generic shoebox model.

RESEM, the Retrofit Energy Savings Estimation Model (Carroll, et al. 1989), is a simulation based tool for estimating the energy savings due to energy conservation retrofits in existing institutional buildings. A fundamental requirement for RESEM is the initial creation of a simulatable building description from minimal user input. This initial description is subsequently reconciled with real utility data to assure that its simulation results accurately match the real building under analysis (see Carroll and Hitchcock, 1993). However, the initial description attempts to account for specifics of building practices and real building characteristics.

The RESEM building description creation process is initiated by the user entering key characteristics of the real building. These characteristics include: building type (e.g., hospital, elementary school, secondary school), building “location (state), initial year of construction, total floor area, and fuel types used in the building. This information is then used along with a set of embedded production rules, a modifiable database of basic building description components, and numeric methods, to generate a complete prototypical building description.

RESEM uses embedded production rules to encode technical knowledge regarding design and construction practices for a variety of building types and construction periods (e.g., pre-1950, 1950-1965, etc.). These production rules are used to assign various characteristics to the generated building based on an extensive set of defaults. The building parameter defaults assigned to an elementary school by the RESEM production rules are shown in Table 2. These include details for such features as wall, roof and window component types, occupancy schedules, HVAC system and plant types, and building use zoning breakdowns.

A user modifiable library, or database, of building elements is incorporated into RESEM to allow definition of building components such as wall, roof, and window types, as well as hourly and monthly profiles, and so-called “activities” that define occupancy, lighting, equipment, sensible loads, and hot water use levels. An example subset of wall construction type definitions is shown in Table 1. The database of building components is fully modifiable from within the RESEM interface.

Numeric methods are used by RESEM to adapt the created building description to the input building size and location. These methods determine overall building geometry and thermal zoning as well as HVAC equipment sizing.

The RESEM implementation of building description generation, as described here, addresses many of the stated requirements for a design aid tool. The method is user controllable by being based on user input high level building characteristics and built from user modifiable building components. The resulting building description is detailed to the level of these “real world” building components, as opposed to only being defined in terms of continuous variables such as U-value. It is also tailored to match the real building by using encoded technical knowledge and numeric methods to adapt the building description to common building practices and site location. Finally, the generation process eases the burden on the user by requiring only minimal input to create a complete simulatable building description.

There are two key limitations to the current RESEM implementation in regard to developing a design aid tool. The first is that the embedded production roles are presently not modifiable by the user. This restricts the variety of building types that can be automatically created as well as the adaptability of the rules to differing common building practices. The second limitation comes from the pseudo-geometry that is defined for the created building description. This limitation is an artifact of the simulation roots of the program. The assumption is that what really matters here is an accurate simulation of the thermal performance of the building, not an accurate geometric representation. RESEM does not deal with daylighting and therefore this assumption is not violated for its specialized application. If lighting and daylighting issues are to be addressed by a design aid tool, an accurate geometric representation is obviously a strict requirement. However, this adds a new level of complexity to the description creation process, particularly if the process is meant to be interactive and user controllable for building footprints other than simple rectangles.

DESIGN GUIDANCE APPLICATION

The point of creating a reference-case building description based on common building practices and the building program, is to explore means of improving its performance. The purpose of a design aid tool is to guide this exploration by making use of established performance-enhancing methods. These methods are generally the distillation of extensive technical research or hands-on experimentation. This guidance may already be available in technical reports, or made more accessible in written design guideline documents. However, application of this guidance requires carefully evaluated adaptation to the building design project at hand.

The automated application of design guidelines therefore requires: 1) the encoding of established technical knowledge, 2) the controllable adaptation of this knowledge to the building at hand, and 3) the accurate evaluation of the resulting design modifications to assure overall building performance improvement. Fulfilling the last of these requirements is the process of using the simulation engine to compare the reference-case building description to an enhanced building design. It is the initial encoding of knowledge and its adaptation that define the problem aspects of automated design guidance.

ENERGY- 10 (NREL, 1995), a design tool for low-rise buildings, is being developed by a collaborative effort between the Passive Solar Industries Council, the National Renewable Energy Laboratory, and the Lawrence Berkeley Laboratory. This tool is targeted toward building designers who wish to incorporate an integrated whole building approach to daylighting, passive solar heating, and low-energy cooling. ENERGY- 10 contains many of the features of a lighting design aid tool discussed above including integration of the DElight simulation engine and a thermal simulation engine, a method for generating a product-level reference-case building description, and an initial implementation for providing daylighting design guidance.

This initial implementation proceeds according to the following design guidance application scenario. The process begins by generating a reference-case building description, using an approach similar to that described above for RESEM. Next, the user is presented with suggested characteristics for a daylighting energy-efficient strategy (EES) for enhancing performance of the reference-case building. The user can accept these suggested characteristics or interactively modify them. These characteristics are then automatically applied to the reference-case building. The two building descriptions (with and without the daylighting EES) can then be simulated to evaluate their overall performance differences. Two critical operations supporting this scenario are the determination of the suggested daylighting EES characteristics, and the automated application of these characteristics to the reference-case building.

A Windows 3.1 dialog displaying an example of the ENERGY- 10 Daylighting EES characteristics is shown in Figure 1. These characteristics include lighting control set point (design illuminance), lighting control type (continuous or stepped dimming), window construction type (representing a product-level building component), and glazing to host surface (or floor) area ratio. These characteristics are independently given for various lighting zone orientations (i.e., north, east, south or west facing, and interior core). The suggested values for each of these characteristics would be adapted to the user's current building project. Lighting control set point and control type are determined from the user entered building type (e.g., office, retail outlet, warehouse). The window construction type is determined from the building site location. The glazing to surface ratio is then determined from the combination of these other characteristics and daylighting guidelines gleaned from two design manuals, the Skylight Handbook Design Guidelines (AAMA, 1987) and the PWC Daylighting Manual (PWC, 1989). The dynamic adaptation of each of these EES characteristics to the current building project is not yet filly implemented in ENERGY- 10. However, the user can freely view and edit these characteristics prior to their automated application.

The application of these EES characteristics to a reference-case building description has been automated in ENERGY-10 for rectangular building geometry. This application process modifies the reference-case description by changing to the EES defined window type and glazing to surface ratios, and by determining perimeter and core lighting zoning geometry (zone floor areas and control point locations). All the user need do is click on a user interface button that tells ENERGY- 10 to apply the Daylighting EES.

This implementation provides a powerful and flexible means of guiding the user toward improved building performance related to daylighting. There is still development work needed to further automate the adaptation of the design guidelines to the current building project. It would also be useful to develop algorithms for automating the application of the EES characteristics to non-rectangular building geometry.

CONCLUSIONS

This paper has explored three requirements for advancing from standalone lighting simulation/analysis tools to simulation-based design aid tools. There are undoubtedly many other requirements not addressed here. However, these three are seen as being significant hurdles to transferring the power of simulation tools, and substantial bodies of technical knowledge regarding energy efficiency, from the research arena to the building practitioner.

Work-in-progress on implementing techniques to address each of these requirements has been discussed in order to further understand both the details of these hurdles and possible solutions for overcoming them. There is still considerable work needed in each of these areas. Simulation engines need to be further tailored to their redefined role within a design aid tool. Work to this end has been identified for future efforts on the DElight engine. Additional flexibility in adapting the automated generation of a reference-case building is needed, particularly with regard to the geometric details of the building. More intelligent and dynamic techniques for presenting design guidance to the user and applying this guidance to a reference building also need to be developed. Lastly, for a design aid tool to be effective, it must bundle all of these technical features into a seamlessly integrated whole that frees the user to focus on the process of design instead of that of operating the tool.

ACKNOWLEDGMENTS

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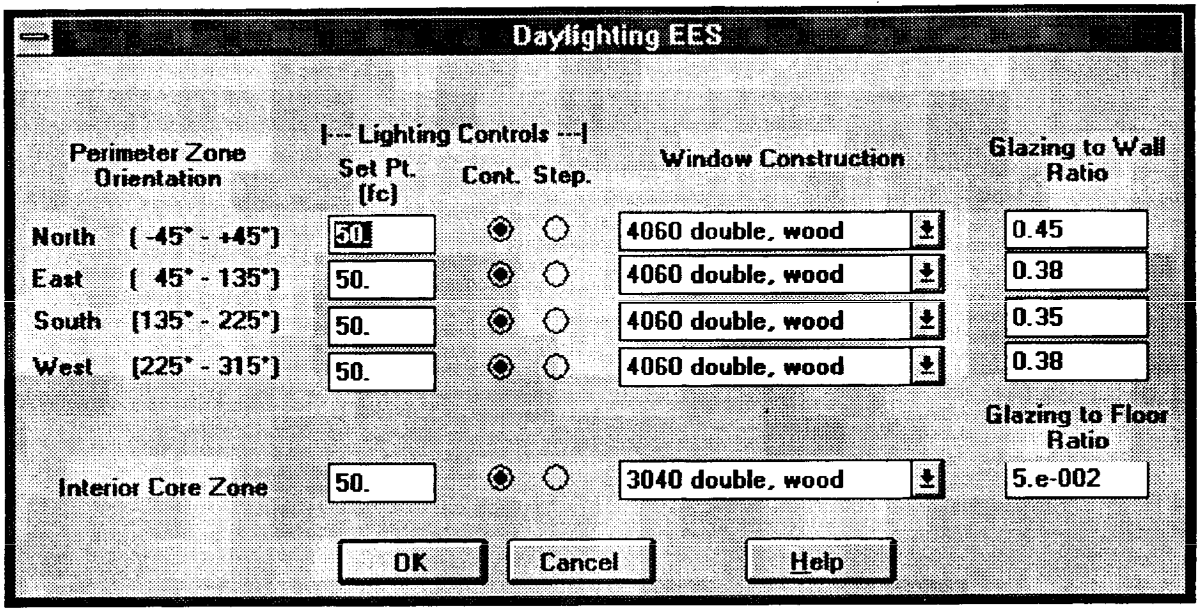
FIGURES AND TABLES



Daylighting EES

Perimeter Zone Orientation	Set Pt. [fc]	Cont.	Step.	Window Construction	Glazing to Wall Ratio
North [-45° - +45°]	50.	●	○	4060 double, wood	0.45
East [45° - 135°]	50.	●	○	4060 double, wood	0.38
South [135° - 225°]	50.	●	○	4060 double, wood	0.35
West [225° - 315°]	50.	●	○	4060 double, wood	0.38
					Glazing to Floor Ratio
Interior Core Zone	50.	●	○	3040 double, wood	5.e-002

Figure 1. Daylighting Design Guideline Dialog from ENERGY-10 (NREL, 1995).

Table 1: RESEM Default Library Wall Constructions (Hitchcock, et al., 1991)

Wall Name	U-Value	Construction Group[a]	Color Correction
12Br0	0.350	E	0.83
8B4br0	0.274	D	0.83
6B4br1	0.250	C	0.83
6B4br5	0.100	B	0.83

[a] See 1989 ASHRAE Fundamentals, Chap. 26, Table 30 for descriptions of these groups

Table 2: RESEM Elementary School Prototypical Building Description Parameters
(Hitchcock, et al., 1991)

Parameter	Pre-1950	1950 -1965	1965-1975	Post-1975
Walls	12Br0	8B4br0	6B4br1	6B4br5
Roofs	6Cr3	Mr6	Mr6	Mr10
Windows	1p-1/8c[a]	1p-1/8c	1p-1/8c	1p-1/8c
Percent Glass	30	60	40	30
Weekday Hours of Operation	7AM-3PM	7AM-3PM	7AM-3PM	7AM-3PM
Saturday Hours of Operation	none	none	none	none
Sunday Hours of Operation	none	none	none	none
Months of System Equipment Operation	Sept-May	Sept-May	Sept-May	Sept-May
Months of Occupancy	all[b]	all[b]	all[b]	all[b]
Infiltration rate (air changes per hour)	1.0	1.0	0.8	0.5
Heating Plant Type	boiler	boiler	boiler	boiler
Heating Plant Efficiency (percent)	75	75	75	75
Cooling Plant Type (if applicable)	centrifugal[c]	centrifugal[c]	centrifugal[c]	centrifugal[c]
Cooling Plant COP	4.5[c]	4.5[c]	4.5[c]	4.5[c]
HVAC System Type	CVVT[d]	CVVT[d]	CVVT[d]	VAV[e]
Percent Outside Air	100	30	30	20
System Air Changes per Hour	2.0	6.0	6.0	6.0
System Fan Power (W/cfm)	0.4	0.4	0.4	1.2
Occupied/Unoccupied Heating Setpoints	72/55	72/55	72/55	72/55
Occupied/Unoccupied Cooling Setpoints	76/90	76/90	76/90	76/90
Classroom Zone % of Total Floor Area	90	90	80	80
Classroom Zone Floor to Floor Height[f]	12	12	12	12
Classroom Zone Number of Floors	2	1	1	1
Classroom Zone Occupancy (ft^2/per)[g]	100	100	100	100
Classroom Zone Lighting (W/ft^2)[g]	1.5	1.5	1.5	1.5
Classroom Zone Elec Equipment(W/ft^2)[g]	0.1	0.1	0.1	0.1
Classroom Zone Hot Water (gal/day)[g]	0.6	0.6	0.6	0.6
Multipurpose Zone % of Totl Floor Area	10	10	20	20
Multipurpose Zone Floor - Floor Height[f]	24	24	24	24
Multipurpose Zone Number of Floors	1	1	1	1
Multipurpose Zone Occupancy (ft^2/per)[g]	100	100	100	100
Multipurpose Zone Lighting (W/ft^2)[g]	0.8	1.0	0.8	1.0
Multipurpose Zone Elec Equip (W/ft^2)[g]	0.1	0.1	0.1	0.1
Multipurpose Zone Hot Water (gal/day)[g]	0.6	0.6	0.6	0.6

[a] This window type is Single Pane, 1/8 in. clear glass, U-Value = 1.1, Shading Coefficient = 1.0

[b] Occupancy, lighting, and electrical equipment levels are adjusted by applying the multipliers found in monthly schedule *sch-occ*(i.e., 1.0 from September through May and 0.1 from June through August)

[c] For small schools with air conditioning, the cooling plant type will be reciprocating with a COP of 3.6

[d] Constant Volume Variable Temperature

[e] Variable Air Volume

[f] This floor to floor height is corrected for a hung ceiling in zone volume calculations

[g] Listed values are varied over a 24 hour day by applying the multipliers found in hourly schedule *se2-wkd*(i.e., 1.0 from 9AM to 3PM and 0.0 from 3PM to 9AM)