

DELIGHT: A DAYLIGHTING AND ELECTRIC LIGHTING SIMULATION ENGINE

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ABSTRACT

DELIGHT is a simulation engine for daylight and electric lighting system analysis in buildings. DELIGHT calculates interior illuminance levels from daylight, and the subsequent contribution required from electric lighting to meet a desired interior illuminance. DELIGHT has been specifically designed to integrate with a building thermal simulation on a timestep basis, for whole-building analysis. This paper describes the simulation methods used in DELIGHT and some of the key details of software implementation.

INTRODUCTION

DELIGHT is a simulation engine for daylight and electric lighting system analysis in buildings. DELIGHT calculates interior illuminance levels from daylight, and the subsequent contribution required from electric lighting to meet a desired interior illuminance. A simulation can be performed for a single point in time and exterior daylight availability, or on a timestep basis for a specified run period using either theoretical or measured weather data. Interior daylight levels can be calculated for a single reference point, or for multiple points throughout a space to analyze the spatial distribution of light. DELIGHT has been specifically designed to integrate with a building thermal simulation on a timestep basis, for whole-building analysis.

The evolving DELIGHT engine has a heritage from several sources. Versions 1.x were based on the DOE-2 daylighting algorithms [Winkelmann, 1983], which were well known, tested, and had fast execution times. Slightly modified versions of this engine have been successfully linked with a variety of other software development projects. Version 2.0 of DELIGHT, under continuing development, enhances the original version with the radiosity interreflection calculations from SUPERLITE [Selkowitz et al., 1982], and newly developed algorithms for analyzing complex fenestration systems (CFS). This version is being integrated with EnergyPlus [Crawley, et al., 2001] to provide an alternative daylighting analysis to the existing methods within that simulation engine.

DELIGHT VERSION 1.X

Simulation Methods

DELIGHT Versions 1.0 through 1.5 were fundamentally a port of the DOE-2 daylighting algorithms with some modifications. These existing algorithms were used because they were well known and tested, and had fast execution times. Modifications were made to provide flexibility in running the simulation, calculating additional output, and integrating the analysis with other software tools.

The overall approach taken within the DOE-2 daylighting algorithms is to pre-calculate a set of daylight factors for each of a predefined series of sun positions, and then interpolate between these daylight factors at each timestep during the simulation run period. Each daylight factor is a ratio of interior horizontal illuminance at a specified reference point (i.e., interior location), to exterior horizontal illuminance for a particular sky condition (e.g., overcast or clear) and an illuminance source (i.e., sky or sun). A weighted combination of the interpolated values of these daylight factors at each timestep is used to simulate the actual mixed sky condition. This calculation ultimately results in the interior illuminance level at each defined reference point. A description of the installed electric lighting and control system is then used to determine the required electric light contribution to meet a defined illuminance set point.

A detailed description of the algorithms used to perform these calculations has been given elsewhere [Winkelmann, 1983]. Validation studies have been undertaken that compare the results from these algorithms implemented within the DOE-2 software with illuminance measurements made in scale models placed within a sky simulator. The differences for clear and overcast sky conditions are generally less than 15% except at positions very near or far away from an aperture where the split-flux algorithms over predict interreflected illuminance [Winkelmann and Selkowitz, 1985]. The implementation of these algorithms within DELIGHT has been validated through direct comparison to produce the same results as DOE-2.

It should be noted that there is not a detailed representation of the electric lighting system within these algorithms. Only installed lighting power per unit area, and design illuminance level are specified. The implicit assumption is made that the installed lighting system produces the design illuminance at full power input. The electric lighting system control is defined simply as either a linear or stepped relationship between input power level and output illuminance level for purposes of determining the required electric light needed to supplement the available daylight.

The approach of interpolating between pre-calculated daylight factors for a limited number of sun positions greatly reduces the time of computation for an annual simulation. Since this approach is not dependent on luminance distribution data for the actual sky vault at each timestep, it also allows the data available from typical meteorological weather files to be used for the timestep simulation. It does however introduce the uncertainties associated with combining theoretically calculated sky luminance distributions to estimate actual skies.

One primary motivation in developing the initial version of DELight was to support the simulation of the spatial distribution of interior daylight as well as the temporal distribution. To accomplish this the DOE-2 limitation of at most two interior reference points was relaxed to allow the specification of an arbitrary number of reference points. This limit is established within DELight at the time that the program is compiles, and is generally increased to at least 100 points per lighting zone. A related modification within DELight is the distinction that is made between a lighting zone and a thermal zone. One or more lighting zones can be defined within DELight that may map to a single thermal zone within a thermal simulation engine such as DOE-2 or EnergyPlus.

A tradeoff was made in DELight in order to increase these limits in the DOE-2 algorithms without dramatically impacting the computation time of the simulation. The tradeoff is that DELight combines the contribution from all apertures in a lighting zone into a single set of daylight factors for each reference point. This is as opposed to the DOE-2 method that maintains separate sets of daylight factors for each aperture-reference point pair. The impact of this tradeoff is that DELight does not support dynamic aperture control within the timestep simulation. For example, shades cannot be opened and closed at each timestep based on a threshold parameter like glare index.

The incremental versions of DELight v1.x have arisen from ongoing maintenance of the code, relatively minor code enhancements, and modifications tailored to specific integration applications.

Software Implementation

A primary motivation in developing the first version of DELight was to allow flexible integration of the implemented daylighting analysis methods with other simulation software. To this end, DELight Version 1.0 was written in highly portable ANSI C, and modularized to allow either standalone execution or relatively easy integration with other software modules. Most compilations of DELight have targeted the Windows® environment and have been created as a dynamic link library (DLL). A very simple user interface has also been created as a standalone host executable to allow testing and debugging as well as end-user simulation runs. This interface allows a user to create/edit text input files, run the simulation engine with editable run control parameters, and view/edit text output files.

Slightly modified versions of the DELight engine have been successfully linked with three software development projects: ENERGY-10 [Balcomb and Beeler, 1998] and the Building Design Advisor (BDA) [Papamichael et al., 1997] in the Windows environment, and the AEDOT-1 [Brambley and Bailey, 1991] prototype in a UNIX environment.

The modifications made to DELight to accommodate these different software hosts have largely involved reformatting the output written from within the engine. These integration efforts have also involved modifications to the manner in which input is provided to the engine, switching between input via a formatted ASCII external data file, to dynamic memory population of the DELight internal data representation from within the host software that calls the DELight engine DLL. The input format of both weather data and glazing characteristics has also been specially tailored to each host software tool.

The application programming interface (API) to DELight v1.5 is a single function call to the engine that includes a set of parameters that both identify input to the simulation engine and control its execution. Table 1 lists these API parameters.

Table 1. DELight V1.5 API Parameters.

Parameter	Description
sWxName	Weather file pathname
sInputName	Input file pathname
sOutputName	Output file pathname
sW4LibNmae	Window4 library file pathname
dCloudFraction	Fraction of sky covered by clouds
iNumAlts	Number of sun position altitudes
dMinAlt	Minimum sun position altitude
iNumAzms	Number of sun position azimuths
dMinAzm	Minimum sun position azimuth
iStartMonth	Beginning month of run period
iStartDay	Beginning day of run period
iEndMonth	Ending month of run period
iEndDay	Ending day of run period
iYear	Year of run period

DElight v1.5 can be executed with or without using a weather data file as input. If no weather file name is given, the daylighting simulation will be executed for each hour of one day each month using theoretical sky conditions for the site location and hourly sun position. Also under this circumstance, the entered fraction of sky covered by clouds will be used for each hour of each day. This value must be within the range of 0.0 for clear skies and 1.0 for overcast skies and is not used if a weather file is input. DElight v1.5 expects ASCII Typical Meteorological Year 2 (TMY2) data files as input.

The format details of DElight input and output files are documented in the manual that accompanies the DElight program. See the Current Status section below for more information on acquiring DElight.

Performance data for glazing materials can be input to DElight v1.5 either within the input file (using either the original DOE-2 glazing types or Energy-10 glazing types) or from another external data file based on the format of the Window4 Glazing Library. If Window4 data are to be used, then the pathname of the library file must be given in the API call.

The number of sun positions for a DElight v1.5 simulation can be varied from a single position to a maximum of twenty total positions (maximum of 4 altitude angles and 5 azimuth angles). These sun positions will be automatically determined based on a uniform grid defined by the building location and the number of, and minimum, angles specified in the API call. If a single sun position is specified in the API, only the daylight factors preprocessor will be executed and the results from theoretical skies for the specified sun position will be output. If a timestep calculation is desired, either with or without weather data, then a full set of sun positions should be used for the preprocessor. Using fewer sun positions will decrease accuracy without significantly reducing execution times.

The run period is defined by the beginning and ending month and day of the month given in the API call. The timestep for DElight v1.5 is set at one hour. Execution time for an hourly annual simulation of a simple single room zone with one window is approximately one second on an 800MHz CPU.

DELIGHT VERSION 2.0

Simulation Methods

The development of DElight v2.0 has focused on three significant enhancements to earlier versions of the simulation engine. The first of these is the enhancement of the treatment of the interreflected component of interior illuminance distribution. The second enhancement addresses the need to analyze more complex fenestration systems than simple windows and flat skylights. The third enhancement

is a substantial reworking of the internal handling of geometry.

Interreflected Light

DElight v1.x use the so-called split-flux method for calculating the effect of interreflected light within an interior space [Winkelmann, 1983]. This method evenly distributes interreflected light throughout a space by using area weighted average surface reflectance values for upper (i.e., ceiling and upper wall) and lower (i.e., floor and lower wall) surfaces within the space. This is a useful approximation if the illuminance at critical reference points is dominated by the contribution from direct daylight. However, as previously mentioned, this method tends to over predict interreflected light at positions very near or far from apertures.

To improve the accuracy of analyzing the spatial distribution of light, the split-flux method has been replaced with a radiosity method in DElight v2.0. The radiosity method discretizes each reflective surface within a space into subdivisions that reflect incident light to all other visible surface subdivisions in the space. The radiosity algorithms used in DElight v2.0 are based on those developed in SUPERLITE and have been described in detail elsewhere [Modest, 1982; Selkowitz et al., 1982; Kim et al., 1988]. Radiosity methods are well suited to this particular application because they produce rapid solutions with high photometric accuracy at levels of geometric subdivision that are too coarse to be suitable for visual scene rendering. These algorithms provide improved accuracy while not imposing a significant penalty in computation time, especially given present and ongoing computer performance increases. Validation studies using a three-way comparison between the DOE-2 and SUPERLITE algorithms, and illuminance measurements in scale models within a sky simulator have shown improved accuracy from the radiosity algorithms over the split-flux algorithms for positions close to or far from apertures [Winkelmann and Selkowitz, 1985].

Complex Fenestration Systems

The second significant enhancement to DElight v2.0 is the addition of new algorithms to analyze the interior daylight contribution from complex fenestration systems (CFS). A CFS is a fenestration system that is more complex than the simple windows and flat skylights that DElight has been capable of analyzing in the past. Examples of these more complex fenestration systems include geometrically complicated lighting/shading devices such as light shelves and roof monitors, and exotic light-redirecting glazing materials such as prismatic and holographic glass [IEA-SHC Task 21, 2000].

There do exist tools that can analyze the daylight contribution from CFS for a specific room / environment case [LBNL, 2002; Ward, 1994]. The treatment of CFS within DELight differs from them by allowing CFS to be efficiently analyzed on a time-step basis and in a manner that can be directly integrated into whole-building energy analysis tools. This capability requires computational efficiency that is not currently available using those other analysis tools.

The CFS algorithms build on existing methods from the computer graphics industry and academia, and from ongoing work done as part of the daylighting research within the International Energy Agency Solar Heating and Cooling Program [Carroll, 1999; IEA-SHC, 2002].

The analysis of CFS within DELight is based on the characterization of these systems using bi-directional transmittance distribution functions (BTDF). A BTDF is a set of data that have been pre-calculated or pre-measured for a given CFS, which capture the ratios of incident to transmitted light for a range of incoming and outgoing directions. As illustrated in Figure 1, a BTDF can be thought of as collapsing a CFS to a “black box” that is represented geometrically as a flat two-dimensional light-transmitting surface that is treated as an aperture surface in the room description. For each incoming direction across the exterior hemisphere of the CFS, it transmits varying portions of that light at multiple outgoing directions across the interior hemisphere of the CFS. The two-dimensional CFS “surface” and directional hemispheres are “abstract” in that they may not literally correspond to actual CFS component geometric details.

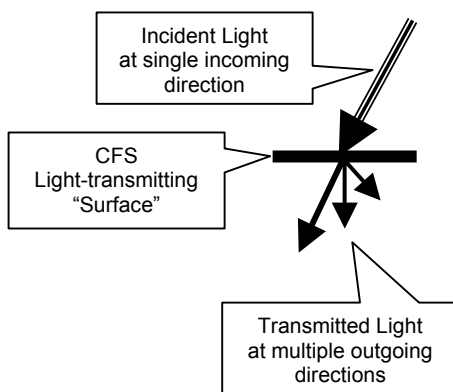


Figure 1. Transmitted light to incident light ratios

The pre-calculated or pre-measured BTDF for a CFS is independent of its final position and orientation within a building. Once a specific instance of a CFS aperture has been positioned within a building, the incident light from all exterior sources across the CFS exterior hemisphere must be integrated over all

incident directions for each relevant transmitted direction to determine the light transmitted by the CFS surface in that direction. The light transmitted by the CFS aperture is then distributed to surfaces in the room according to its non-uniform directionality, and becomes part of the radiosity analysis like traditional apertures such as windows, as illustrated in Figure 2.

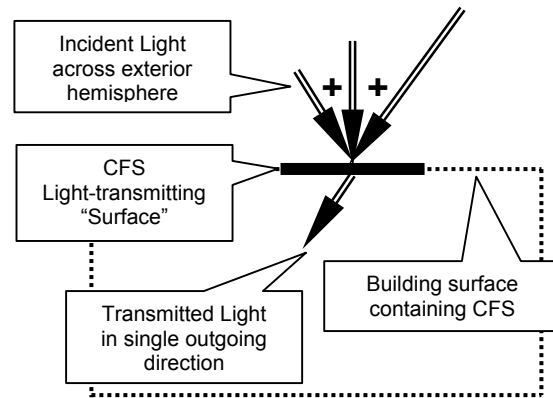


Figure 2. Integrated incident light for a single transmitted direction.

The algorithms for this BTDF treatment of CFS in DELight are still under development. The initial algorithms in DELight v2.0 are limited to two theoretical CFS types, Beam and Lambertian, which were primarily developed for diagnostic purposes during software development. These are simplified CFS types that, unlike the representation of CFS using BTDF that is illustrated above, should be thought of as light-emitting surfaces whose characteristics can be completely user specified within a lighting zone.

A Beam CFS can be thought of as an ideal flashlight generating a directional, conical beam with a sharp cutoff at a specified cone angle. A Lambertian CFS can be thought of as a directional diffuse emitter with adjustable “focus” determined by a cone of a specified angle. The luminous flux density (i.e., lumens/unit area of the CFS at an angle of incidence equal to the emitting angle) emitted into the interior space through one of these CFS can be specified by the user. The primary emitting direction for these two CFS types is “aimable” through user input specifications.

Additional CFS types will be added following the implementation of the algorithms for handling the data associated with the BTDF characterizations and the external illuminated environment. These algorithms include methods for integrating the incident daylight from the exterior hemisphere surrounding each CFS, and calculating the subsequent transmitted daylight contribution to each visible surface subdivision in the space.

Geometry

DElight v1.x use the geometric representation and geometry processing methods implemented in DOE-2. These methods are, for the most part, based on an underlying assumption that all surfaces (walls, apertures, floors, ceilings) are rectangular in shape. Furthermore, all user input of geometry is entered in relative terms. That is, apertures are relative to their host walls/ceilings, which are in turn relative to their bounded lighting zones, which are relative to the building. These assumptions place constraints on the allowable complexity of building geometry, and on the flexibility with which this geometry can be input to DElight.

To address these constraints, a set of C++ geometry classes has been developed into a library for use in DElight 2.x. The existing geometric representation and processing within DElight is incrementally being migrated to make use of this new class library. In DElight v2.0 only the processing of CFS take advantage of this library. Future versions of DElight will make use of this library for all geometric representation and processing.

Software Implementation

DElight v2.0 has been developed within the Microsoft Visual C++ 6.0[®] environment. However, effort has been made to maintain the portability of the code to other environments. For example, the C/C++ Standard Library [Josuttis, 1999] has been used rather than the Microsoft-specific libraries.

A standalone version of the software has been developed under the Windows[®] environment to allow testing and debugging as well as individual simulation runs. The DElight engine itself has been built as a Windows Dynamic Link Library (DLL). The host user interface has been developed as a Windows executable that displays a single dialog box providing user input of the engine API parameters. The user interface also includes the ability to view and edit ASCII text input and output files within a text editing window.

The API of DElight v2.0 still consists of a single function call with a parameter list similar to that shown in Table 1, with three additional parameters. The additional parameters include the user specified number of subdivisions applied to simple apertures and reflective surfaces, and the number of iterations to be used in the radiosity calculations. This revised API can be used to call the simulation engine from any Windows application.

Integration of DElight v2.0 into other software basically requires generating a DElight v2.0 input file defining the building to be simulated, providing access to external weather and glazing data files in the expected format, and making a call to the engine with the appropriate parameter values. The run

control options for DElight v2.0 remain fundamentally the same as those for v1.5. Execution time for v2.0 for an hourly annual simulation of a simple single room zone with one window, using 100 subdivisions on each interior reflecting surface and 5 iterations of the interreflection calculation is under 10 seconds on an 800MHz CPU. While appreciably slower than v1.5 using the split-flux implementation, this is still not an unreasonable execution time overall. Execution times for the currently implemented theoretical CFS types is comparable to that of a simple window.

The only significant difference in executing v2.0 is the new input required for defining CFS instances within a building. As noted above, only two theoretical CFS types have been preliminarily implemented in v2.0 as of the writing of this paper, Beam and Lambertian. Since these CFS types do not account for exterior luminance conditions, it only makes sense to simulate these fenestration systems for a single static case. A timestep simulation would not produce meaningful results since these CFS types do not emit dynamically changing light. Execution times for CFS types that account for exterior luminance conditions will undoubtedly be longer than for these theoretical types.

The standard output file generated by DElight v2.0 is largely an echo of the input along with the values for each building element that are calculated as part of the daylighting simulation. For each input Exterior Surface including Shades, the output includes average luminance values under overcast skies, and for each sun position under clear skies. For each Interior Surface the output includes direct and total luminance values under overcast skies and for each sun position under clear skies, for each surface subdivision. For each input Reference Point the output includes illuminance and daylight factor values from the daylighting factors preprocessor for overcast skies, and for each sun position under clear skies; and monthly average daylight illuminances for each hour of the day. Note that hourly daylight illuminance values can also be output, but are not written to the standard output file. For each Lighting Zone the output includes monthly average electric lighting energy reduction fractions for each hour of the day. These values represent the average fractional electric lighting energy *savings* for each hour of the day over the course of each month.

CURRENT STATUS

Complex Fenestration Systems

At the time of writing this paper (February 2003) DElight v2.0 has been developed to the point described above. The implementation of the BTDF treatment of complex fenestration systems is still under development and should be available in

DELight v2.1. This implementation will include a draft format for BTDF data files, which will undergo modifications as international work in this area progresses [IEA-SHC Task 21, 2000]. This implementation will also include methods for calculating the integration of incident light across the exterior hemisphere of a CFS placed within the building, and the transmitted light in any outgoing direction.

Integration with EnergyPlus

DELight v2.0 is being integrated with EnergyPlus as of the writing of this paper. It is planned that DELight will remain a separate module with calls to EnergyPlus to retrieve its required input, and calls from EnergyPlus to perform its calculations and pass calculated output back to EnergyPlus for integration with the whole-building simulation. This integration is intended to provide an alternate daylighting analysis option to the algorithms already available within EnergyPlus v1.0.3 [Lawrie et al., 2002]. An EnergyPlus user will then select which daylighting simulation methods to use based on the building and systems under analysis.

Software Availability

DELight v2.0 is currently available to end users in executable form. The package contains the DELight v2.0 DLL, the simple user interface host Windows executable, documentation on input and output, and example input/output data files. DELight is also available to software developers for integration with other software tools. Contact the software developers for more information on acquiring DELight.

FUTURE PLANS

Plans for future development of DELight include refinements of the existing implementation as well as several extensions. Two of these extensions deal with the treatment of electric lighting system components, and of CFS components. These extensions are briefly presented here.

Electric Lighting System Simulation

As mentioned above, the description of the electric lighting system within DELight is still limited to an overall installed lighting power per unit area that is assumed to provide a specified design illuminance level at the workplane. Furthermore, the electric lighting control system is defined simply as either a linear or stepped relationship between input power and output illuminance. A more complete and accurate approach would support the analysis of luminaires and a realistic treatment of more complex control system interactions.

The treatment of CFS with DELight v2.x following the integration of incoming light over the exterior

hemisphere, is closely analogous to the representation of electric lighting luminaires using candlepower distribution data. It would thus be a relatively simple extension to apply the implemented CFS methods to the treatment of luminaires. Having this enhanced analysis of luminaires would also support a more sophisticated treatment and analysis of control systems.

CFS Directional Luminance Distribution

Another extension that is a potential outcome from the treatment of CFS is a standalone processor that would calculate and output directional luminance distribution data for a CFS and a given exterior daylight availability. These data could be formatted according to standards such as the IES standard for electric lighting luminaires for input into any lighting software tool for analysis.

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