INTEGRATING ADVANCED DAYLIGHT ANALYSIS INTO BUILDING ENERGY ANALYSIS

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ABSTRACT

With electric light accounting for about a quarter of the total energy used in U.S. office buildings (CBECS 2003), there is the potential for substantial energy savings through effective daylight design. However, the generic solar radiation and daylight control calculations in commonly used energy analysis software may be too crude to accurately account for the performance benefits of daylight design in buildings. Additionally, energy analysis tools do not address visual comfort and glare concerns which are critical to the success of a daylight design. Using currently available analysis tools, there is the potential to merge daylight and energy analysis to assess the effectiveness of daylight design strategies while accurately gauging the potential lighting energy savings. This integrated approach described in this paper entails a three step process using the analysis programs DAYSIM (Reinhart 2001, www.daysim.com), DOE-2.2 (www.doe2.com) and evalglare (Wienold 2004) to estimate energy performance and glare potential in buildings.

This paper presents initial application of and results from an office building project that utilized an integrated daylight and energy analyses process. Results from the integrated process are compared against the conventional daylighting control calculation method in DOE-2.2, and the results show a meaningful difference in estimated energy savings between the two calculation methods. This paper also presents the results of a glare probability analysis of one office space.

INTRODUCTION

Interior lighting represents a substantial portion of a building’s overall energy consumption. Efforts to reduce lighting energy use in buildings through technology upgrades and stricter lighting standards have been effective. In 1995, lighting systems consumed 8.2 kWh/sq.ft of energy in office buildings and accounted for approximately 29% of the total energy used in office buildings (CBECS 1995). In 2003, lighting systems consumed 6.8 kWh/sq.ft. of energy in office buildings and accounted for approximately 25% of the total energy use (CBECS 2003). While improvements in lighting technology (ie. LED lights) and improvements in energy standards (ie. ASHRAE 90.1-2007 and 2010) are still being targeted for additional energy reduction, additional energy savings potential may be possible through intelligently controlling lighting systems to respond to available daylight. In order to evaluate the effectiveness of an integrated daylight and electric light design on reducing energy consumption while minimizing glare conditions, an integrated means on accurately assessing the energy performance and glare risk of various daylight design options in buildings is needed.

As noted by Roti and Addison (Roti and Addison 2007), the DOE-2.2 analysis tool uses a simplified approach to daylight analysis, which could result in inaccurate assessment of the effectiveness of daylight design and daylight control strategies. Additionally, existing energy analysis tools incorporate very rough means for accounting for glare. This paper presents a test case of one project in which advanced daylight analysis tools, DAYSIM and evalglare, were integrated into the workflow of eQuest (running the DOE-2.2 engine), an industry-standard energy analysis tool.

METHODOLOGY

General Approach

The fundamental approach for the integrated daylight and energy analysis described in this paper is as follows:

To calculate the energy savings, the authors used DOE-2.2 version 47d (through eQuest 3.63b build 6500 as the interface) as the whole-building energy analysis tool. For the daylight calculations only, the authors substituted the daylight controls schedules created by DOE-2.2 with schedules created based on the more detailed daylight calculations generated by DAYSIM v2.1.P3.
Then, to calculate the glare risk, the authors used evalglare v0.9f.

**DOE-2.2 Daylight Calculation**

DOE-2.2 is an industry standard energy analysis software used in the industry to evaluate the energy performance of buildings. DOE-2.2 calculates the interaction of multiple systems over the course of a typical year to assess relative energy performance in buildings. These systems include the geometry and massing, the façade and envelope, the heating ventilation and air-conditioning (HVAC), the domestic hot water, the electrical, and lighting systems.

The daylighting calculation method in DOE-2.2 uses a simplified approach to calculating the illuminance inside a space from daylight. Using the split-flux calculation method, DOE-2.2 calculates the diffuse component by calculating the Sky Component (SC), External Reflected Component (ERC), and Internal Reflected Component (IRC), and summing up these components to arrive at a Daylight Factor (DF). For a uniform sky condition, the DF calculates the percentage of available daylight that illuminates a point on a horizontal plane.

To calculate the direct component, DOE-2.2 creates a look-up table of twenty evenly distributed points on a sunpath diagram, and interpolates the values between these twenty points.

- The DF calculation is calculated for CIE overcast and clear skies, and so is limited in its ability to account for changing sky conditions.
- The split-flux method is reasonably accurate with square and rectangular spaces, but is not with all types of geometry.
- The split-flux method cannot address moderately complex fenestration systems and light redirecting daylight strategies.
- The split-flux method is reasonable for average illuminance levels in middle of the space, but not good for points close to windows or deep in the space.

For the direct component:
- Sun positions for only twenty points are pre-calculated, about half of which fall outside of the possible sunpath. This results in large portions of the year when the direct component in the look-up table is off by a large margin.

Based on the calculated illuminance values, DOE-2.2 creates a lighting schedule to control the installed electric light system in response to available daylight.

**DAYSIM**

DAYSIM is a stand alone daylight calculation software that uses the Daylight Coefficient (DC) method to quickly calculate the diffuse and direct components of daylight in a space over every daylight hour in a year.

In calculating the diffuse component, the DC approach allows for the use of non-uniform, more realistic skies that vary hour by hour. The DC method divides the sky into multiple small patches (DAYSIM divides the sky into 145 individual patches), and precalculates the percentage of contribution each patch of sky has on a reference point inside a space. Then, for each hour, the sky luminance value of each individual patch is multiplied by the solid angle constant and the DC; the summation of the illuminance contribution of each sky patch provides the equivalent of the sky component, external reflected component, and internal reflected component.

DAYSIM calculates the direct component by pre-calculating the DC of sixty-five sun positions that actually are on the sunpath, and then interpolates the illuminance contribution of the sun from the four closest calculated positions when the sun’s position falls outside of the precalculated positions. The increased number of sun positions further increases the accuracy of the daylight calculations.

![Sunpath diagram showing DOE-2.2's twenty sample sun positions](image)
The Daylight Coefficient approach used in DAYSIM addresses the shortcomings of the Daylight Factor approach used in DOE-2.2.

- DAYSIM uses the Perez all-weather sky to account for the ever-changing sky conditions that are expected to occur in the real world.
- DAYSIM can accurately simulate complex geometry and complex fenestration systems.
- DAYSIM can accurately calculate the daylight levels in any location in a room.
- The direct component is calculated from actual sun positions.

**Evalglare**

Evalglare is a glare assessment tool developed to evaluate glare problems due to daylight in an office. Evalglare is a software based tool that identifies glare sources in a 180 degree fish-eye scene, and evaluates the anticipated magnitude of the glare source. The algorithm in evalglare is based on an empirical study of over 100 test subjects in a controlled office setting who rated whether or not they experienced glare under different conditions, and rated the magnitude of the glare experience.

**Detailed Approach**

**DOE-2.2 Energy Analysis**

For this analysis, an administration building on an academic campus was modeled. A TMY2 file for Syracuse, New York was used for the climate.

Specific to the lighting system, the lighting power densities were assigned on a room-by-room basis. The annual lighting energy consumption for two typical offices were tracked – one open office on the west side of the building (715 square feet), and a single office on the east side of the building (300 square feet). Figure 6 below highlights in turquoise the two specific spaces that were evaluated. For reference, the total building area is roughly 52,000 square feet with office space accounting for 18% of the floor space or 9,500 square feet. The installed lighting power density for the east office was modeled as 0.9 Watts per square foot, and 1.1 Watts per square foot for the west office.

The occupancy schedule of the offices reflected the occupancy of a typical academic office building. See the schedule in Figure 4.
daylight control reduces the power output of the dimming fluorescent fixtures according to the linear curve shown in Figure 5. While this curve does not accurately reflect real ballast and lamp controls, it proves useful as a simplified approach to compare DOE-2.2 daylight controls to the DAYSIM control method.

DOE-2.2 uses this control curve to calculate a daylighting multiplier for each hour of the day based on the available illuminance at the sensor location. These multipliers are then factored into the lighting schedule to reduce the fraction of lights turned on throughout the day.

**DAYSIM Daylight Analysis**

An analogous geometric model of the academic building was built using Ecotect. A horizontal gridpoint was created 2’-6” above the floor, and a DAYSIM analysis was run to create an annual illuminance profile across the illuminance grid. Then, the individual gridpoint on the horizontal gridpoint that corresponded with the location of the daylight sensor in the DOE-2.2 model was identified, and the annual illuminance profile for the specific point was used to develop a daylight responsive control schedule.

The hour-by-hour daylight control schedule generated using DAYSIM was simplified into average daily lighting control schedules for each month of the year. Leaving all other aspects of the energy model the same, the daylight responsive schedule created using DAYSIM was used to replace the daylight responsive schedule created by DOE-2.2.

**Evalglare Glare Analysis**

Using the geometric model used for the DAYSIM analysis, evalglare was used to assess the glare risk in the office spaces. Glare is dependent on the time of day, time of year, and a specific view in a space. Yet in order to assess a daylight design for overall glare risk, a general sense for the frequency and magnitude of glare problems in a space over the course of the year is required. Evalglare evaluates a photometrically accurate fish-eye image of a space (i.e. a Radiance rendering). However, even at relatively low rendering parameters, the time required to render each daylight hour of the year was too great to conduct an hourly glare assessment.
In order to expedite the glare analysis, two weeks in each month were selected, and every other day was evaluated on an hourly basis using evalglare. A fish-eye view camera was placed at a desk in the office, looking across the office so that an overall condition in the office can be captured in a single view. See Figure 7 for the camera view evaluated, and Figure 8 for a sample evalglare analysis image.

![Figure 7 Floorplan of west office space with view arrow used for the glare analysis](image)

Figure 7 Floorplan of west office space with view arrow used for the glare analysis

![Figure 8 Evalglare generated image of the west office](image)

Figure 8 Evalglare generated image of the west office

The authors recognize that this approach of taking a small subset of the total daylight hours in the year may not accurately reflect the glare risk in a space. Yet, in the Syracuse climate where overcast conditions occur for more than 60% of the daylight hours in the year (see Figure 9), it was evident from a preliminary evalglare analysis that when the sky conditions are overcast, glare is not a major concern.

![Figure 9 Seasonal sky cover conditions for Syracuse, NY](image)

Figure 9 Seasonal sky cover conditions for Syracuse, NY

**RESULTS**

**Daylight Control Schedule**

Before running the energy model with the DAYSIM modified lighting schedules, the DOE-2.2 lighting schedules after the daylighting multipliers were compared side by side to the DAYSIM schedules. The graphs below (Figures 10, 11 and 12) show the average daily schedules for March, July, and October for the west facing open office space. Schedules for the two offices were developed for every month of the year.

The general trend shows that for most of the year, the DAYSIM schedules track the DOE-2.2 created schedules, but reduce the lighting schedule fraction throughout the day. See Figures 10 and 12. On average, the daily lighting fraction is reduced by 25% during the school year (with full occupancy) and 15% during the summer months (with reduced occupancy). However, because the DAYSIM schedules are fixed for an entire month and the eQUEST schedules will change daily based on the weather file solar radiation data, the estimated reduction in lighting power fraction does not directly relate to lighting energy savings as shown in the next section.

However, in the summer months (Figure 11), the DOE-2.2 and DAYSIM schedules do not track very well; the DOE-2.2 lighting fraction peaks at times in the day, while the DAYSIM light fractions remains relatively flat throughout the day. The reason for this difference is likely due to the fact that the direct component calculation method in DOE-2.2 interpolates values from sun positions that are outside of the sunpath (see Figure 1), resulting in artificially low daylight illuminance levels.
Lighting system and lighting energy consumption
Details about the lighting systems for the two spaces are given in Table 1 below. The west space is classified as a conference room and as such has a slightly higher installed lighting power density than the east facing office. Occupancy sensors, which turn the lights off 15 minutes after the occupant leaves, are included in both spaces by taking the 10% lighting power density reduction allowed in Appendix-G of ASHRAE 90.1-2007. The west and east spaces have baseline lighting energy consumption of 1.9 and 1.5 kWh/sq.ft./year without daylighting controls, respectively. These values are well below the 2003 CBECS national average for office spaces. This is due to the low installed lighting power densities, occupancy sensors, and reduced operating hours throughout the year based on the school’s holiday and vacation schedule.

<table>
<thead>
<tr>
<th>Space Use</th>
<th>West Space</th>
<th>East Space</th>
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<tbody>
<tr>
<td>Area (sq.f.)</td>
<td>713</td>
<td>296</td>
</tr>
<tr>
<td>Lighting Power Density (W/sq.ft.)</td>
<td>1.1</td>
<td>0.9</td>
</tr>
<tr>
<td>Installed lighting (W)</td>
<td>785</td>
<td>266</td>
</tr>
<tr>
<td>Occupancy Sensors</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Lighting Energy Intensity w/out daylighting (kWh/sq.ft./year)</td>
<td>1.9</td>
<td>1.5</td>
</tr>
</tbody>
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Table 1 Lighting System Details

Figures 13 and 14 compare the monthly lighting energy consumption of the three energy simulations: DOE-2.2 without daylight controls, DOE-2.2 with continuous-off controls, and DOE-2.2 with DAYSIM modified lighting schedules.
Figure 14 Monthly lighting energy use in the east office

For the west facing office space, the DOE-2.2 and DAYSIM models estimate annual lighting energy intensities of 1.2 and 0.8 kWh/sq.ft./year, respectively. This translates to a 32% reduction in annual lighting energy consumption for the DAYSIM method over the DOE-2.2 daylighting method. Month to month, the percentage savings ranges from 30% in the winter months to 40% in the spring and fall months.

For the east facing office space, the DOE-2.2 and DAYSIM models estimate lighting energy intensities of 0.7 and 0.6 kWh/sq.ft./year, respectively. This translates to a 21% reduction in annual lighting energy consumption for the DAYSIM method over the DOE-2.2 daylighting algorithm. Month to month, the percentage savings ranges from 0% in the summer months to 37% in the winter months. These results are presented in Table 2 below.

<table>
<thead>
<tr>
<th></th>
<th>West Space</th>
<th>East Space</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lighting Energy Intensity w/out daylighting (kWh/sq.ft./year)</td>
<td>1.9</td>
<td>1.5</td>
</tr>
<tr>
<td>DOE-2.2 Daylighting Lighting Energy Intensity (kWh/sq.ft./year)</td>
<td>1.2</td>
<td>0.7</td>
</tr>
<tr>
<td>DOE-2.2 Percentage Lighting Energy Savings over Model w/out Daylighting</td>
<td>36%</td>
<td>52%</td>
</tr>
<tr>
<td>DAYSIM Lighting Energy Intensity daylighting (kWh/sq.ft./year)</td>
<td>0.8</td>
<td>0.6</td>
</tr>
<tr>
<td>DAYSIM Percentage Lighting Energy Savings over Model w/out Daylighting</td>
<td>57%</td>
<td>62%</td>
</tr>
<tr>
<td>DAYSIM Percentage Lighting Energy Savings over DOE-2.2 daylighting model</td>
<td>32%</td>
<td>21%</td>
</tr>
</tbody>
</table>

Table 2 Lighting Energy Intensities

The difference in lighting energy performance of the two spaces is due to the amount and orientation of glazing. The west office is 22% glazed and the glazing is part of a sawtooth façade system which places the glazing southwest instead of due west, thereby increasing the number of hours of usable daylight. The DAYSIM algorithm shows increased daylight levels in this space and results in higher savings. The east office is only 13% glazed and the glazing faces due east and has limited daylight exposure; thus, there is little change between the DOE-2.2 daylight and DAYSIM algorithms.

Whole building energy use and interactive effects

While this analysis focused only on two spaces, these two spaces are representative of the rest of the office area on the second floor of the building. From this analysis, it is also possible to examine the effect on cooling and heating energy use in each space and also estimate the energy savings as part of the whole building energy consumption. Figures 15 through 18 below show the effect of daylighting controls on heating and cooling energy.
As expected, the heating energy use increases and cooling energy decreases with decreased lighting energy use. The increase in heating energy offsets about 40% of the lighting energy savings for both spaces with only 3% cooling energy savings.

The building is designed to be a very low energy building with a design energy intensity of 37 kBtu/sq.ft./year. Lighting energy is predicted to be 13% of the overall building energy use and any small reductions will help the project meet this goal. The estimated energy savings for the whole building using the DAYSIM algorithm is 0.35 kBtu/sq.ft./year more than the savings calculated using the DOE-2.2 daylighting algorithm. This equates to an approximate 1% annual energy savings for the building.

Glare analysis

In the mostly overcast climate in Syracuse, the frequency and magnitude of glare conditions were minimal. Due to resource and time limitations, an evalglare analysis was conducted for the west office only.

For the west office, from September through early April, disturbing or intolerable glare occurred for two to three hours in the mid-afternoon. Otherwise, glare conditions were imperceptible for other times of the year. See Figure 19 at the end of this paper. Green cells indicate times when glare is not a concern. Orange cells indicate times when glare may be noticeable. Red cells indicate times when glare is expected to be intolerable. Due to the geometry and orientation, it was deemed that in the east office, intolerable glare conditions will occur for three to four hours in the mid-morning hours from September to early April.

Given the low frequency of glare conditions, and the fact that glare screens would be installed in the windows, the design team determined that glare conditions did not pose a high risk to the offices, and would be manageable.

Discussions

For this specific academic office building, the integrated daylight and energy analysis process resulted in a substantial difference in the energy consumption in the individual spaces. In the west space, the DAYSIM method resulted in an additional 32% (0.4 kWh/sq.ft./year) reduction in annual lighting energy consumption, and in the east space, a 21% (0.1 kWh/sf/year) reduction. On a space-by-space basis, this level of savings is significant.

Relative to the overall building, the DAYSIM approach resulted in about a 0.35 kBtu/sq.ft./year reduction in energy consumption. This level of savings may be too small to justify the additional time and effort that was required to implement this alternative process. However, the office space square footage on this particular project is only about 18% of the overall building square footage (approximately 9,500 square feet of office space in a 52,000 square foot building). Given the relatively small percentage of space that is expected to benefit from the daylight controls evaluated, the savings are notable.

While the overall building energy savings were modest on this project, on a project where the daylight controls impact a larger portion of the overall building (such as a high-rise tower project in which daylight-controlled office spaces represent the vast majority of the building square footage), it is likely that the overall building energy savings would be a higher percentage of overall building energy consumption.

In terms of glare evaluation, the relative infrequency of glare conditions, in conjunction with an adjustable glare control strategy, obviated the need for further detailed glare study.

In terms of the additional time required for this alternative process, the initial simulation using the DAYSIM process required about 1.6 times more days.
than a standard DOE-2.2 process would have taken. A standard DOE-2.2 modeling effort for this project would have required about five days, but using the DAYSIM approach took eight days. The vast majority of the additional time was spent in building the DAYSIM model, and in processing the results from DAYSIM into a format that DOE-2.2 would accept. Once the DAYSIM model was created, and templates to process the DAYSIM results were created, subsequent analysis required approximately 30 minutes to an hour. Thus, the initial time investment in implementing such a process is immense, but once the proper tools are created, subsequent runs are much more manageable. Further automation of the process is possible, meaning that the additional time would still be required to develop a DAYSIM model, but not necessarily to process the results.

**Limitations**

The main limitation of this study is that this is an evaluation of just one project in one climate. In order to draw general conclusions, a range of case studies in various climates will be required. Additionally, the integration of DAYSIM calculation into the DOE-2.2 simulation procedure has not been validated. While DAYSIM is a validated daylight simulation tool, the process described above requires further validation to determine if the additional savings predicted are likely to be realized.

The DAYSIM approach was not simulated for every daylighted space. Rather, two typical spaces were evaluated, and the savings were multiplied out to the appropriate square footage based on orientation.

This study used a basic Continuous Off Daylighting Control strategy in order to ensure that the results between the DOE-2.2 and DAYSIM approach were directly comparable. Moving forward, using the DAYSIM approach, more sophisticated performance curves can be simulated to more closely account for the performance characteristics of the daylight control systems that are currently available.

**CONCLUSIONS**

Integrating more advanced daylight analysis into DOE-2.2 may enable projects to more accurately assess the energy benefits of daylight design. On a space basis, the potential energy benefits may be significant. On an overall building basis, the energy savings may be marginal.

The process is not validated. Future work would require validation of the process, and potentially incorporating the more advanced algorithm into energy analysis tools so that the process can be completed with little to no additional time investment.

**ACKNOWLEDGMENT**

This paper is the result of simulations completed during spring 2010 during the design development phase of the building design process. Thank you to Paul Stoller and Nico Kienzl for providing the additional time and resources to explore and develop this alternative method. Thanks also to members IBPSA-NYC who provided initial comments on the methods and results of this study.

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Figure 19 Glare risk in west office. Green indicates that glare is imperceptible; orange indicates that glare is perceptible; and red indicates that glare is intolerable.