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PERFORMANCE MODELING OF DAYLIGHT INTEGRATED PHOTOSENSOR-CONTROLLED LIGHTING SYSTEMS

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ABSTRACT

Some building energy codes now require the incorporation of daylight into buildings and automatic photosensor-controlled switching or dimming of the electric lighting system in areas that receive daylight. This paper describes enhancements to the open-source Daysim daylight analysis software that permit users to model a photosensor control system as it will perform in a real space, considering the directional sensitivity of the photosensor , its mounting position, the space and daylight aperture geometry, window shading configuration; the electric lighting equipment and control zones; exterior obstructions; and site weather conditions. System output includes assessment of the daylight distribution in a space throughout the year, the photosensor's ability to properly track the daylight and modify electric lighting system output, and the energy savings provided by the modeled control system. The application of daylight coefficients permits annual simulations to be conducted efficiently using hourly or finer weather data time increments.

1 INTRODUCTION

With the current movement toward more green and sustainable buildings, daylighting is being promoted as the primary light source for buildings, with electric lighting being configured to supplement daylight when and where daylight fails to provide sufficient interior lighting. Emerging building energy and green building codes (California Energy Commission 2008, International Code Council 2009, ANSI/ASHRAE/USGBC/IES 2009) are now requiring certain levels of daylighting or sizes of daylight apertures and are moving toward daylight specification that applies annual metrics using typical meteorological year (TMY) weather data and corresponding simulated sky conditions. Metrics such as daylight autonomy (DA) (Reinhart, Mardaljevic, Rogers 2006) or spatial Daylight Autonomy (sDA) (IESNA 2011) or some derivative of these (Nabil and Mardaljevic 2005) are likely to be applied in the future.

To achieve electric lighting energy savings in daylit spaces, it is necessary to reduce or turn off some or all of the electric lighting within the space. This can only occur in those areas that receive ample amounts of daylight, which may require separate dimmed or switched lighting zones in these areas. To ensure that only the minimum amount of electric lighting necessary will be applied, a photosensor-based lighting control system is applied to electric lighting control zones in the daylit areas to sense the total amount of light within a space, or the amount of daylight entering a space, and control those zones accordingly. One of the limitations of these systems is that photosensors used for this purpose are typically mounted on the ceiling rather than on the work plane (since the latter may lead to occupant tampering, or photosensors that are inadvertently obstructed or covered). A barrier that surely has affected the application of these systems has been the lack of tools to investigate and optimize the performance of these systems. Architectural Energy Corporation (2008) developed one of the first standalone tools (SPOT) that could analyze photosensor system performance, but this software offers limited geometry and daylight modeling capability. This paper describes a new photosensor and electric lighting system modeling capability that has been implemented into the Daysim software (Reinhart 2011). The new modules permit the analysis of electric lighting and the modeling of integrated photosensor lighting control by considering the spatial response of the photosensor and standard photosensor control algorithms for the dimming and switching of the electric lighting system (Rubinstein, Ward, and Verderber 1989; RPI 2007). Dasysim's analysis modules permit a user to address a wide range of space geometry and aperture configurations to gain valuable feedback on both daylighting and control system performance. The Daysim software was previously developed by Reinhart and others and is available through an open-source license and free download. The enhancements described in this paper significantly expand the performance of Daysim in its standalone version (some features of Daysim are available through a Rhino plugin, but not all of those described in this paper).

One of the key attributes of this software is that it can be used to address spaces of high complexity, since the calculation engine applied is *Radiance* (LBNL 2011), which offers a wide range of materials and flexible space geometry. Existing Radiance utilities permit model conversion from CAD software. Complex electric lighting system layouts can also be applied. Complex fenestration can also be addressed. Currently, in Daysim, this is addressed through standard ray-tracing techniques, although a newly developed capability of Radiance to apply bidirectional transmittance functions (Ward et al. 2011) will likely be incorporated in the future.

2 CALCULATIONS

2.1 Daysim Input

The input data required by Daysim include the following:

1. Enter room, daylight aperture, and relevant exterior geometry.
2. Enter the geometrical and material descriptions of operable window shading devices, which may include up to three different settings on two different groups of windows.
3. Enter TMY weather file for the site.
4. Enter occupancy conditions for the entire year. Partial occupancy is permitted to account for intermittent use of a space.
5. Specify an array of calculation points that covers the work plane.
6. Enter the photosensor-controlled and the non-photosensor-controlled electric lighting systems (luminaire type via an IES formatted file, ballast power to light output characteristics, luminaire locations, light loss factors, etc.)
7. Enter the photosensor's spatial sensitivity and mounting location, select one of the available control algorithms, and calibrate the control algorithm to a critical work plane point for a selected daylight condition (date and time and its daylight condition indicated in the TMY data file).

A sample space that has been used for all figures presented in this paper is shown in Figure 1.

2.2 Daylight Calculations in Daysim

The Radiance calculation engine used in Daysim applies a reverse ray-tracing lighting analysis algorithm to model the illuminance at a specified array of analysis points as well as to compute the signals at individual photosensors.

Daysim computes annual daylight values at an hourly or smaller time increment by computing daylight coefficients for 145 different patches of the sky (Figure 2). Daylight coefficients (Tregenza and Waters 1983) define the relationship between the luminance of a sky patch and the illuminance at an interior work plane point through a simple multiplier that permits fast processing of sky conditions across all times of the year, and are derived from a single detailed ray-trace solution. This is done by tracing rays from each analysis point through a requested number of bounces. When a ray eventually strikes one of the sky patches, its contribution from that patch is recorded. Through a slightly different approach, daylight coefficients are determined at approximately 85-90 solar positions (hourly across the solstices, equinox and two other days as shown in Figure 3), uniformly spread across the sun's annual range of positions for that site. Performance at the position of the solar disk at each time step condition are then interpolated from these positions. Final interior analysis points are then derived by multiplying and summing the products of the daylight coefficient at each sky patch times its luminance as well as an interpolated daylight coefficient for the solar position times the sunlight beam intensity. These calculation approaches are described in more detail in Bourgeois, Reinhart, and Ward (2008).

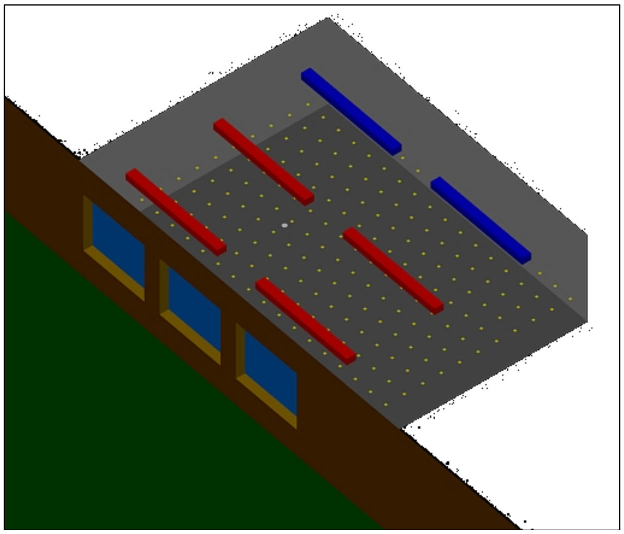


Figure 1: Cutout view of an example classroom space showing windows, work plane calculation grid, controlled/dimmed (red) and non-dimmed (blue) lighting zones, and ceiling mounted photosensor (centered within dimmed lighting zone).

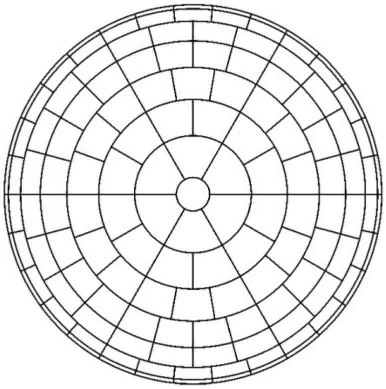


Figure 2: Orthogonal projection of the sky dome showing the 145 sky patches used in Daysim

The daylight coefficient approach is also used to determine the signal at a photosensor at the given time steps across each day of the year. Separate photosensors are used to control electric lighting zone output and to apply shading devices on windows. The enhanced version of Daysim permits three different shade positions/configurations on each of two different window groups. In addition to having shade positions dictated by an open-loop photosensor reading, shades can also be controlled by solar profile angle (the shadow line of the sun in a vertical plane perpendicular to a façade), or by a combination of photosensor reading and solar profile angle. In the combined condition, the photosensor signal is used to assess when the sky is overcast so that shades are not applied even though the sun may be at a position where shades would otherwise be required.

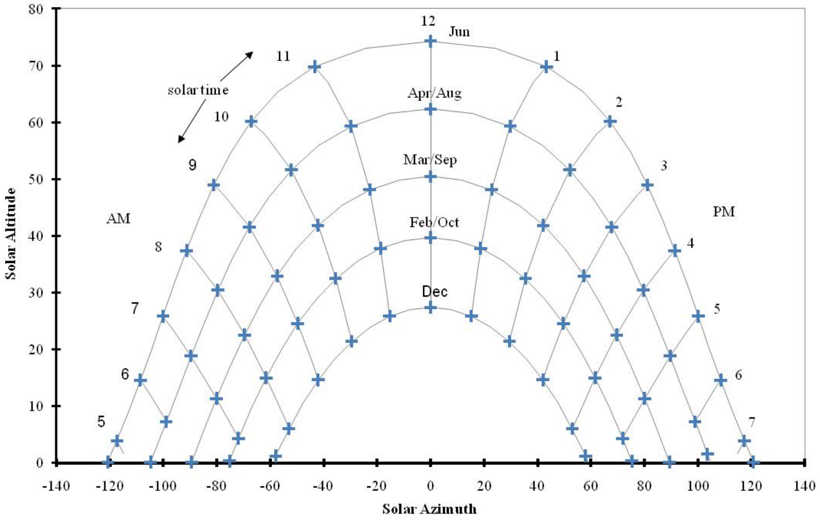


Figure 3: Location of the solar disk daylight coefficient positions for 40N latitude

For photosensor modeling, a hemisphere of variable transmittance is placed around a conventional illuminance analysis point. The photosensor's sensitivity distribution is imported through an XML sensor file which contains values at a series of horizontal and vertical angles that represent the angular response function across an entire hemisphere. The transmittance of the hemisphere created within Daysim is equivalent to the photosensor's sensitivity divided by the corresponding sensitivity of a cosine distribution at each angular position, since the illuminance calculation applied to the photosensor signal calculation already assumes a cosine distribution. Future modifications will permit photosensor distributions to extend beyond a single hemisphere, which is necessary for photosensors that have a protruding (convex) lens.

3 PHOTOSENSOR CONTROL ALGORITHMS

Daysim 3.0 is capable of controlling the lighting in a single zone from a single photosensor using one of the following standard control algorithms, which are found in many commercially available systems.

- Closed-loop proportional control (with or without light shutoff once the dimming level reaches the minimum output permitted by the ballast)
- Closed-loop integral reset control (with or without light shutoff)
- Closed-loop switching
- Open-loop proportional control (with or without light shutoff)
- Open-loop switching

Future enhancements will likely include the ability to have multiple independently photosensor-controlled lighting zones within a space, each controlled by a different photosensor, and the ability to control multiple zones from a single photosensor, which is a capability provided by a few commercially available control systems. The ability to apply customized control algorithms is also planned for the future.

3.1 Control Algorithm Calibration

To compute the annual energy savings that can be achieved with a photosensor-based lighting control system, it is necessary to calibrate the photosensor control system to align the selected control algorithm with the actual space conditions. This calibration process, in effect, provides information on the magnitude of signal that is to be associated with a given output condition for the controlled lighting zone. In a real space, this calibration should be performed for a point within a space that is deemed to be the most critical. That is, if the target illuminance is satisfied at this point, then it is satisfied at all other task locations of importance. The enhanced version of Daysim assists the user in selecting where to locate this point by providing contours of the required dimmed zone electric light output level across a space (Figure 4). The critical work plane point is usually located between the dimmed lighting zone and the non-dimmed lighting zone where the required output from the controlled group of luminaires is greatest when considering the presence of daylight. In a real space, this location is the position where an illuminance meter would be placed to calibrate the lighting control system.

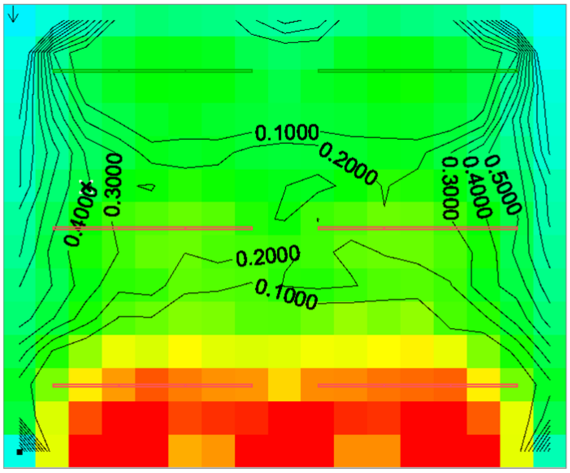


Figure 4: Contours of required dimming levels for the control zone derived from analysis points distributed across the work plane. The critical work plane point is located just beyond second row of luminaires and near the side wall for a controlled zone that consists of the two rows closest to the window.

In most spaces, desired values of illuminance (target values) are based on the visual tasks that are performed within a space. Task illuminance can be delivered by both electric light and daylight, however a sustainable design goal is often to provide as much of this light as possible through the use of daylighting. At the same time, the work environment must be visually comfortable and the environment appearance pleasant, so proper design and the application of shading devices are critical considerations.

Control algorithm calibration is performed within the software in a manner similar to how it is performed in a real space. First, a daylight condition (date, time and the associated weather/daylight conditions from the TMY file) must be selected, along with the location of the critical work plane point. The desired critical point illuminance level must then be entered. With a closed-loop proportional control algorithm, both a nighttime and daytime value must be entered. The daylight condition should deliver enough daylight to the space so that the desired dimming level is near the minimum level provided by the ballast (but not below it). Shades can be at any desired setting for system calibration. The resulting dimming level that achieves the target illuminance value and the corresponding photosensor signal establish the control algorithm signal to light output relationship to be applied at all other times of the year.

3.2 Annual Simulations using the Control Algorithms

Once the photosensor signals are determined for the controlled and non-controlled lighting zones for each time period throughout the year, the algorithms can be applied to determine the controlled zone setting in terms of either its dimming level or operating condition (on or off in the case of photosensor-based switching). Dimming levels from a full annual simulation are then used to determine the associated lighting system power levels from ballast power to light-output data that have been entered for the ballast-lamp combination being used. The annual energy consumption and savings are then tallied for each month of the year based on these power levels and space occupancy conditions. The only omission in the current software is the potential impact of spectral differences between daylight and electric light. The magnitude of these differences is likely to be small, but ultimately depends on the spectral response of the photosensor optics and its detector.

One challenge with photosensor control systems is knowing how well the signal received by the photosensor is able to track the daylight level within a space, and in particular at the critical work plane location. Since the magnitude and distribution of daylight admitted to a space changes significantly across the year due to varying solar positions, sunlight intensity and beam penetration into a space, cloud conditions, and sometimes changing ground conditions (e.g., with snow), the sensor's position and field of view affect its signal reading and ultimately its ability to properly track the amount of daylight being delivered to the critical work plane location (Mistrick and Sarkar 2005).

3.3 Control Algorithm Equations

Equations applied to the different control algorithms are provided below, with photosensor signal (S), ballast factor (BF), and algorithm slope setting (M) applied for the nighttime (nt), calibration setting (cal), daylight (dlt), dimmed zone (dz), and any non-dimmed (nd) lighting in the space.

3.3.1 Closed-loop Proportional Control

This algorithm requires two points on which to base the lighting control algorithm. The first is a nighttime setting that configures the maximum ballast factor, which can be the maximum possible or a lower setting if desired, while the second applies a daylight condition that sets a dimming level, BF_{cal}, for a given photosensor signal reading, S_{cal}, that will be present when the electric lighting control zone is dimmed to provide the desired task illuminance at the critical work plane point. These two points then set a linear relationship between the photosensor signal and the dimming level. This line is assumed to extend out to a signal where the control zone will either be held at a specified minimum output level, or turned off to save energy. See Figure 5.

To apply the control algorithm through the hourly (or finer) daylight conditions across the entire year, the following equations are then applied to determine the BF (dimming level) at a given daylight condition.

The ballast factor at equilibrium must satisfy the following equation.

$$BF = BF_{nt} + M\,S_{dlt} - M\,S_{dz}\ \left[\frac{(1-BF)}{BF_{nt}}\right]$$

Solving this equation for the ballast factor (dimming level), we then have an equation that defines performance under this control algorithm.

$$BF = \frac{[BF_{nt} + M\,S_{dlt} - M\,S_{dz}\ ]}{\left[1 - M\frac{S_{dz}}{BF_{nt}}\right]}$$

Where: $M = [BF_{nt} - BF_{cal}] / [S_{nt} - S_{cal}]$

In addition, if BF from the above equation is less than BF_{min}, then BF = BF_{min}, with full shutoff also possible beyond this point.

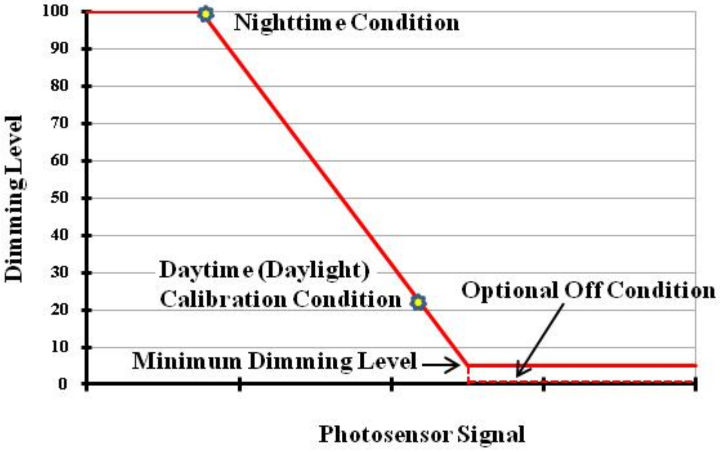


Figure 5: Dimming curve for a closed-loop proportional control algorithm. Both a nighttime calibration and daytime calibration are required. The daylight condition for the latter should provide a strong photosensor signal and a dimming level near the system's minimum.

3.3.2 Open-Loop Proportional Control

This algorithm assumes that a photosensor is mounted so as to experience no response from the electric lighting system that is being controlled. As such, when the photosensor receives no signal (i.e., when there is no daylight), the electric lighting system is set to its maximum output. Still, it is possible that a photosensor for such a system could be located such that it receives input from the electric lighting system. For this reason, the algorithm applied in Daysim considers the nighttime signal to be zero, then dims along a linear path to a calibration setting which assigns a dimming level to a given photosensor signal. The signal and BF pairings that define this linear relationship are (0, BF_{nt}) and (S_{cal}, BF_{cal}).

The control algorithm applied to the hourly data considers the possible influence of the electric lighting systems by applying the following equations to establish the ballast factor at each time step. The first equation is the fundamental equation listing the three signal inputs to the control algorithm, while the second solves this equation for the dimming level (BF) at equilibrium.

$$BF = BF_{nt} + M\,S_{dlt} + M\,S_{nd} + M\,S_{dz}\left[\frac{BF}{BF_{nt}}\right]$$

$$BF = \frac{[BF_{nt} + M\,S_{dlt} + M\,S_{nd}\ ]}{\left[1 - M\frac{S_{dz}}{BF_{nt}}\right]}$$

Where: $M = [BF_{nt} - BF_{cal}] / [S_{nt} - S_{cal}]$. If the photosensor is located outdoors, then S_{nd} and S_{dz} are zero. As in the previous case, if BF < BF_{min}, then BF = BF_{min}, with full shutoff beyond this point also an optional control system feature.

3.3.3 Closed-Loop Integral Reset Control

This algorithm attempts to hold the photosensor signal at a constant value by dimming the electric lighting system as daylight increases the photosensor signal, and then increasing the electric lighting level as daylight levels decrease.

The algorithm for this type of control is as follows. For calibration purposes, the photosensor signal value to be applied must be selected. Some systems perform self-commissioning, and may use the nighttime electric lighting signal for control purposes. This has been shown to be problematic, since the photosensor signal to work plane illuminance ratio (S/E) in most installations is higher for daylight than for electric lighting. Calibrating the control system under a daylight condition will increase the level of the targeted control signal and will delay the onset of dimming while significantly reducing the chance of overdimming (providing too low of an electric light level).

The control algorithm is designed to satisfy the following equation by raising or lowering the controlled lighting zone output.

$$S_{cal} \;=\; S_{dlt} + S_{nd} + (S_{dz}) * \left[\frac{BF}{BF_{nt}}\right]$$

Determination of the BF for this control algorithm is then

$$BF \;=\; [(S_{cal} - S_{nd} - S_{dlt}) \,/\, S_{dz}] \;*\; BF_{nt}$$

Where BF_{nt} is the ballast factor associated with the dimmed zone signal, S_{dz}. Some ballasts may not have a maximum ballast factor of 1.0, in which case the ballast factor BF_{nt}, the full or nighttime setting must be included as shown. If $BF < BF_{min}$, then $BF = BF_{min}$, with full shutoff also possible beyond this point.

3.3.4 Closed-loop and Open-loop Switching

For photosensor-based switching, both a closed- and open-loop configuration are available. In these situations, there must be a dead-band between the signal that turns the controlled lighting zone off and a lower signal that will turn this zone on. For the closed-loop arrangement, this difference must be greater than the signal provided by the electric lighting system that is controlled by the photosensor. The On-Off control is accomplished through the following pseudo code.

```
If ZoneStatus = ON then
If (   $S_{dlt} + S_{nd} + S_{sw}$   >   $S_{off}$ )  ZoneStatus = OFF
Else
If (   $S_{dlt} + S_{nd}$   <   $S_{on}$ )  ZoneStatus = ON
Endif
```

4 DAYSIM OUTPUT

Once the photosensor control system's performance is processed through each time step across the year, the user is able to evaluate the system through a number of different Daysim output features.

First, it is possible to view the total illuminance across the work plane calculation points at any of the times considered in the analysis (Figure 6). The dimming level or switching condition for the dimmed zone is indicated, along with the window group shading device settings.

Annual daylight metrics can be viewed to assess the overall performance of the daylighting system and to aid in selecting the lighting equipment to be controlled by a photosensor. Daylight autonomy (DA), spatial daylight autonomy (sDA,) continuous daylight autonomy (cDA), and Useful Daylight Illuminance (UDI) may each be viewed. See Figure 7.

Other graphical information that is provided include time plots of the illuminance or dimming level for the controlled electric lighting zone. The algorithm-derived values are plotted against optimum dimming level values that are the dimming level required to exactly maintain the desired target illuminance at the critical work plane point that was applied in calibrating the control system. The length of time considered in these graphs can be a day, week, or month, and can be changed between the illuminance at the critical point and an average across all work plane points. Note that average values are relatively meaningless in daylighting designs that produce non-uniform distributions since a combination of high and low values may average out to a desired value, but this value does not show that certain areas within a space may be deficient.

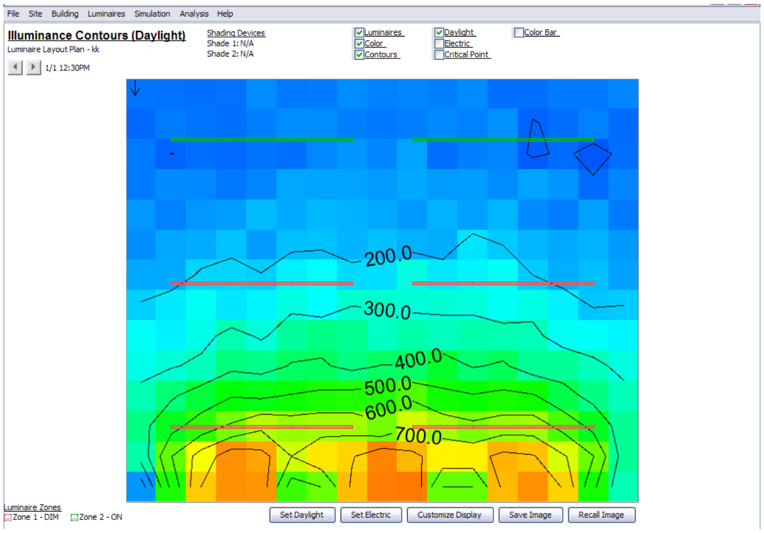


Figure 6: Contours showing daylight levels in lux for a single daylight condition. The room has three windows along the bottom edge of this floor plan.

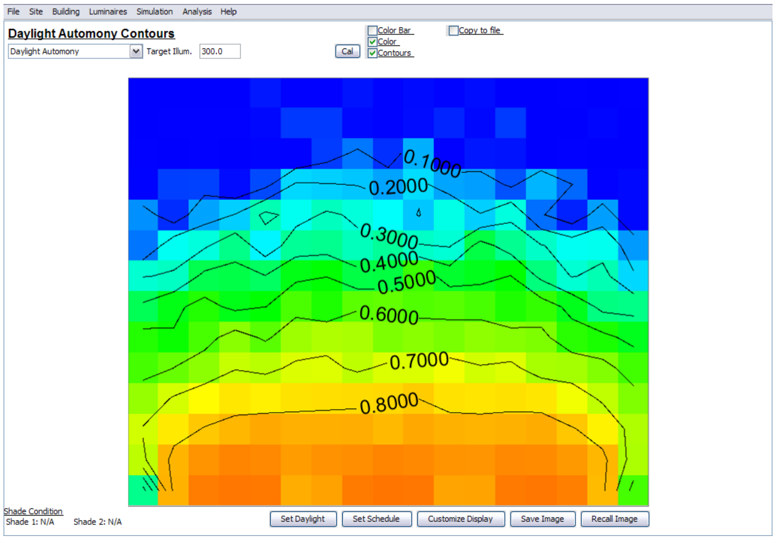
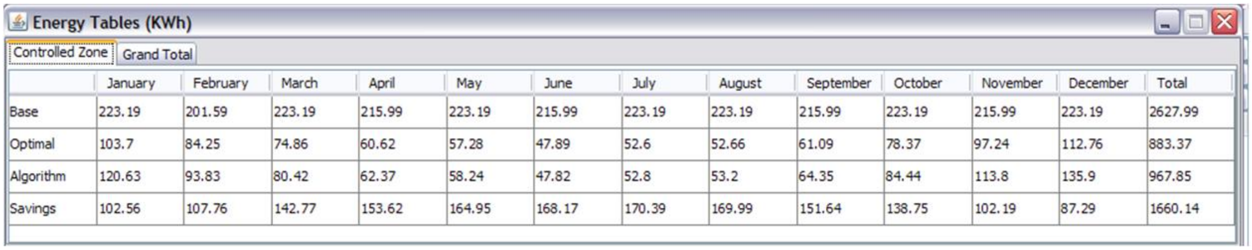


Figure 7: Daylight Autonomy contours for a 300 lux target condition

Energy data that is derived from the photosensor control system is printed in a table that can be toggled between the entire lighting system in the space and only that portion which is controlled by the photosensor (Figure 8). Values of the energy required by the optimized control condition, and the energy consumption and lighting energy savings presented by the photosensor-controlled lighting system with the calibrated control algorithm, are provided for each month of the year and for the year as a whole.

One of the most important evaluative relationships that is displayed by the software is an optimum dimming level versus photosensor signal graph showing the relationship between these two parameters for all occupied times at the critical work plane point (Figure 9). If the critical point is properly selected, performance at this point should provide a good overall electric light setting for the space. If the resulting curve illustrates a strong linear relationship, then a linear proportional control algorithm should work well. If an integral reset control algorithm is being considered, then this linear relationship would ideally be a vertical line, otherwise the control algorithm, which will only dim along a vertical line, will need to be calibrated to place this line toward the high signal end of this clustered data to avoid overdimming the electric lighting system as daylight begins to enter a space. Setting the control signal for an integral reset sensor at the nighttime lighting signal (full light output condition) will result in significant over-dimming since it will place the vertical control curve at the left side of the data set (Mistrick et al. 2000).



	January	February	March	April	May	June	July	August	September	October	November	December	Total
Base	223.19	201.59	223.19	215.99	223.19	215.99	223.19	223.19	215.99	223.19	215.99	223.19	2627.99
Optimal	103.7	84.25	74.86	60.62	57.28	47.89	52.6	52.66	61.09	78.37	97.24	112.76	883.37
Algorithm	120.63	93.83	80.42	62.37	58.24	47.82	52.8	53.2	64.35	84.44	113.8	135.9	967.85
Savings	102.56	107.76	142.77	153.62	164.95	168.17	170.39	169.99	151.64	138.75	102.19	87.29	1660.14

Figure 8: Energy table showing monthly energy costs with no dimming (base case), optimal dimming based on critical work plane point, and algorithm dimming control. Savings are based on the algorithm.

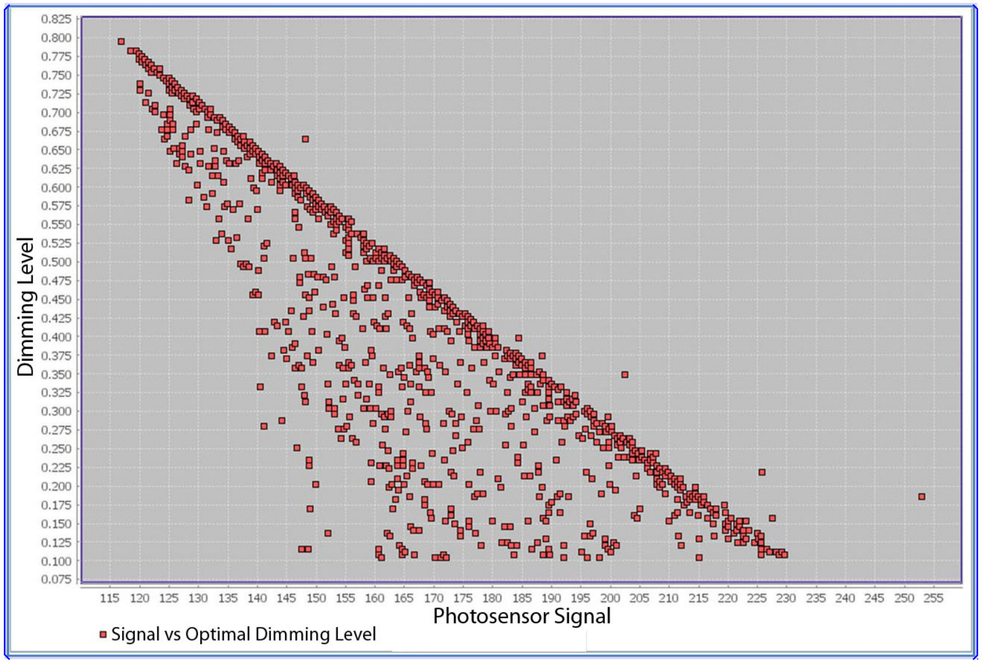


Figure 9: Scatter plot of dimming level versus photosensor signal for different daylight conditions across the year

A wide scatter of points indicates that consistent photosensor control will be difficult to achieve, since multiple daylight work plane illuminance conditions are associated with the same photosensor signal. If such a system is installed, work plane levels can be maintained at the target level or higher by calibrating the system to a daylight condition that has a very strong photosensor signal (a point on the right edge of the scatter plot). The difficulty in calibrating an installed photosensor-controlled system involves not knowing what daylight condition provides a strong photosensor signal to work plane illuminance value S/E , which can also vary with time of the year.

If the photosensor is mounted directly above, or within the direct beam, of an indirect luminaire it controls, the optimum dimming level versus photosensor signal graph will have a slope that goes downward to the left, indicating that a lower signal is needed to establish an optimum condition as daylight is added to the space.

A graphical approach to assessing performance across the entire year is provided through a threshold condition contour plot (Figure 10). The user selects an illuminance level and whether conditions above or below that value are of interest. Daysim will then plot the fraction of the operating hours that each point in the room meets this threshold condition. This analysis can be used to assess the amount of time that a control system overdims the lighting equipment, providing low levels of illuminance in critical task areas, or to assess the maximum illuminance conditions provided by a daylighting system, or the levels provided by a combination of daylight and electric light.

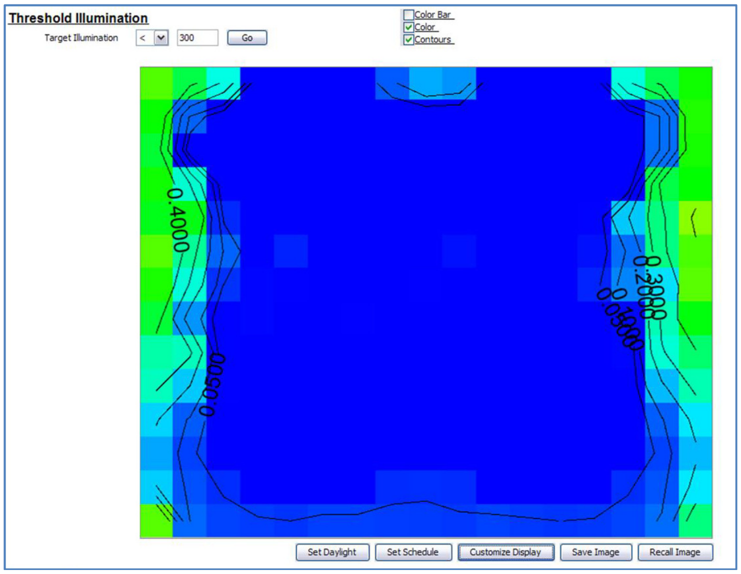


Figure 10: Image of a threshold illumination graph showing the percentage of occupied time that points across the work plane lie below 300 lux

5 SUMMARY/CONCLUSIONS

The Daysim software is designed to provide a capability to model extensive information about the performance of a daylight delivery system, including the application of shading devices when required, as well as the ability of a photosensor-controlled electric lighting system to properly adjust the lighting within a space in response to daylight. This tool can be used to address aspects of photosensor control that previously could not be modeled, such as photosensor placement, control algorithms, its spatial response function, energy savings potential, the impacts of shading devices and direct sunlight penetration and others. Hopefully, the availability of such a tool will lead to a better understanding and application of these systems, which are the key to achieving energy savings with the increased emphasis on sustainable design and on the application of daylight as a primary light source for building interiors.

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