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A simplified method to estimate energy savings of artificial lighting use from daylighting

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Abstract

This paper provides a simplified analysis method to evaluate the potential of daylighting to save energy associated with electric lighting use. Specifically, impacts on daylighting performance are investigated for several combinations of building geometry, window opening size, and glazing type for four geographical locations in the United States. Four building geometries with various window-to-floor areas, along with different glazing types have been analyzed. It was determined that for most commercial buildings with glass transmittance values above 0.5, increasing window area to floor area ratio above 0.5, daylighting does not provide significant additional lighting energy savings. A direct correlation has been established between window transmittance and window area on annual lighting reductions. A model is proposed to estimate lighting energy savings given perimeter area, window area, and window type. Verification and validation of the model's predictions are demonstrated using results from building energy simulation as well as experimental data.

Keywords: Artificial lighting; Daylighting; Energy savings; Simplified method

1. Introduction

Commercial buildings in the United States consume over one-third of the nation's primary energy. Artificial lighting is estimated to account for 25%–40% of this energy consumption [1]. Over the last three decades, several measures have been considered to reduce electricity use associated with artificial lighting. The use of compact fluorescent lamps, installation of occupancy sensors, and better design strategies to minimize the number of fixtures are commonly utilized energy efficiency measures. These measures can achieve substantial energy and cost savings for both new and retrofitted buildings. Though beneficial, these measures require the continuous use of artificial lighting to illuminate buildings.

As an alternative to artificial lighting, daylighting offers a lighting source that most closely matches human visual response and provides more pleasant and attractive indoor environment. It is reported that daylighting improves student performance and health in schools [2]. Recently, there has been an increasing interest among architects and building designers to incorporate daylighting as a means to reduce energy use in buildings [3,4]. Most commercial facilities operate during daylight hours, enabling them to take advantage of an abundant natural light resource.

However, surveys have shown that daylighting strategies are not commonly incorporated in commercial buildings [1,5]. For instance, only 10% of US commercial buildings have some daylighting schemes while almost 50% of the buildings are equipped with energy efficient lamps and ballasts [1]. The lack of simplified evaluation tools, capable of providing information on the suitability of daylighting and its potential to save energy, is considered as one major reason for the reluctance of building professionals in incorporating daylighting features in their design.

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Several detailed simulation tools are available to evaluate the benefits of daylighting such as ADELINE [6] and SUPERLITE [7]. However, these simulation tools require lengthy input process and are too time-consuming to use for most architects and designers. Some models have been developed to predict energy savings for different fenestration designs [3,8]. These models require several calculation steps and are specific to one site or one climate zone. This paper presents a simplified analysis method that can be used as a pre-design tool to assess the potential of daylighting in saving electricity use associated with artificial lighting for office buildings.

In addition, the paper presents results of an analysis that provides useful insights on the relationship between building perimeter, floor area, glazing, window area, and their effects on artificial lighting energy use. The effects of these parameters are investigated for various US cities with diverse climatic conditions. DOE-2.1E, a whole building simulation tool, is used to determine the effects of daylighting on lighting electricity use for typical office buildings [9]. First, the modeling approach is described. Then, selected results from a series of parametric analyses are discussed. Finally, the development of a simplified tool for estimating energy savings from daylighting is presented with results from both verification and validation analyses.

2. Modeling description

The analysis is based on a typical three-story 40,000 square-foot office building having various geometries. It should be noted that the study presented in this paper focuses solely on the electricity savings from artificial lighting reduction, and does not address the effects on the heating and cooling systems. In order to simplify later discussions, the following building parameters are defined:

- A_f—Total floor area of the building.
- A_p—The total perimeter floor area based on an office depth of 12 ft (3.7 m).
- A_w—Total window glazing area for the building.

2.1. Building models

Four building models were selected for the analysis. Typical three-story 40,000 ft^2 (3716 m^2) office buildings were considered with four different geometries. The first model considers a square building whereas the other three models have an increased exposure on the north and south facades while keeping the floor area constant. Fig. 1 provides a representation of the building models considered in the analysis. Typical densities and schedules for office buildings are used to model occupancy, lighting, and equipment.

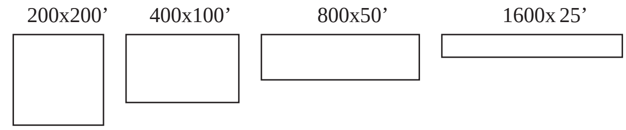

Fig. 1. Building geometries considered in the analysis.

2.2. Shading

Shading is a difficult attribute to model. Personal preferences effect occupant deployment of shading strategies. For this analysis, interior movable shades are modeled in conjunction with a maximum glare value of 22 and a maximum solar heat gain of 30 Btu/ft^2-h (95 W/m^2) [3]. If either of these thresholds is surpassed, shading is used.

2.3. Artificial lighting

Recessed fluorescent troffers were used to represent standard commercial installations. We chose to use only one typical office lighting schedule (correspondent to 8:00 am to 6:00 pm occupancy) to make the analysis repeatable and consistent. Lighting density was set at 1.3 W/ft^2 (14.0 W/m^2) in accordance to ASHRAE/IES standard office value [10].

2.4. Daylighting

Daylighting was modeled for offices on the north, east, west and south sides of the building. The chosen office dimensions were 12.5 ft (3.8 m) wide, 12 ft (3.7 m) deep, and 9 ft (2.7 m) from floor to ceiling. A single daylight control sensor was placed in the center of the room, that is, 8 ft (2.4 m) from the exterior wall. Continuous dimming was selected as the method of daylighting control with a 50 fc (500 lx) minimum [11].

3. Parametric analysis

The analysis presented in this paper encompasses various types of modern commercial buildings. The different geometries allow for the characterization of buildings with various perimeter areas and floor areas. Window to wall area ratio was set to vary from 0 (no openings) to 1 (glazed walls). Due to the vast selection of windows, four different glazing types with varying light transmittance were selected and analyzed. The intent was to obtain a wide range of transmittance values to get a broad representation of available products.

Different geographical locations were evaluated to determine relative differences associated with variations

Table 1
Window transmittances and range of A_w/A_p and A_p/A_w ratios used in the parametric analysis

Glazing	Label	Visible transmittance	Window to perimeter floor area ratio (A_w/A_p)	Perimeter to total floor area ratio (A_p/A_f)
Clear	Glaze 1	0.781	0–0.7	0.23–0.96
Blue	Glaze 2	0.505	0–0.7	0.23–0.96
Gray	Glaze 3	0.381	0–0.7	0.23–0.96
Reflective tint	Glaze 4	0.073	0–0.7	0.23–0.96

in weather and latitude. The four cities selected were Atlanta, Chicago, Phoenix, and Denver. Chicago and Atlanta are cloudier than the two western cities and are at different latitudes. Phoenix and Denver both receive a relatively large amount of sun and are also at different latitudes.

The different glazing types and window areas were modeled in conjunction with the four geometries and four geographic locations. Table 1 lists the window areas and glazing types used in the parametric analysis.

4. Parametric analysis results

The simulation results showed that substantial lighting energy reduction could be achieved from harvesting daylight. Total building lighting savings is primarily a function of the perimeter office space area, the window area, and window transmittance. The relative effects and correlations between the different parameters are summarized in this section. In the discussion of the results, the following normalized parameters are used:

- A_w/A_p: window to perimeter floor area. This parameter provides a good indicator of the window size relative to the daylit floor area.
- A_p/A_f: perimeter to total floor area. This parameter indicates the extent of the daylit area relative to the total building floor area. Thus, when $A_p/A_f = 1$, the whole building can benefit from daylighting.
- Percent energy savings, f_d: fraction of the annual artificial lighting energy consumption saved through the use of daylighting.

4.1. Window area to perimeter floor area

This section focuses on the effects of the window to perimeter floor area ratio, A_w/A_p, on lighting energy reduction. For all window types and geographic locations, it is found as expected that an increase in the A_w/A_p ratio results in a higher savings of lighting energy use. Fig. 2 shows the effects of increasing the A_w/A_p ratio for a set of glazing types when the building has a square geometry ($A_p/A_f = 0.23$) and is located in Atlanta, GA.

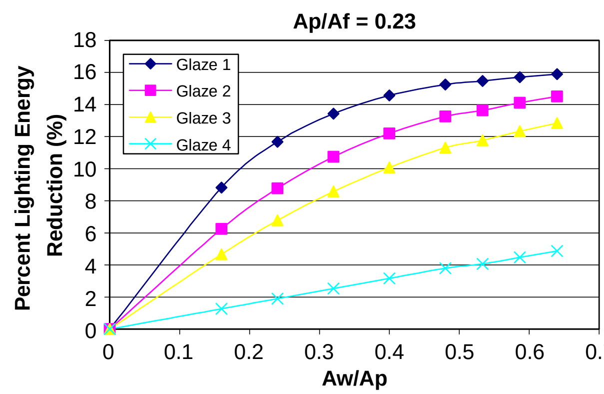

Fig. 2. Energy savings relative to window area for a square building in Atlanta, GA.

For other building shapes, similar results are obtained. However, greater savings can be achieved as the perimeter-to-floor are ratio, A_p/A_f, is increased. The relative magnitudes of savings can be seen in Fig. 3 where the effects of increasing the A_w/A_p ratio are illustrated for various values of A_p/A_f ratios, given a clear glazed window.

Increasing the window area had a diminishing effect on energy reductions for clear windows. Window to perimeter floor areas greater than 0.5 showed little additional lighting energy reduction for building geometries with an A_p/A_f ratio greater than 0.5. Building designers should be aware of the limits that increasing window area may have on electrical lighting reduction. These limits can easily be noted from the results illustrated in Figs. 3–6 for different gazing types and building geometries.

4.2. Transmittance

The transmittance of the windows has a significant impact on daylighting induced energy savings. As the transmittance of the glazing is reduced, the lighting energy savings is also reduced. The tinted windows resulted in energy savings that were linearly dependent on window area, contrary to the diminishing returns behavior observed with the higher transmittance glazing. Fig. 6 shows the effect of widow area on energy reduction for a tinted window in Atlanta, GA.

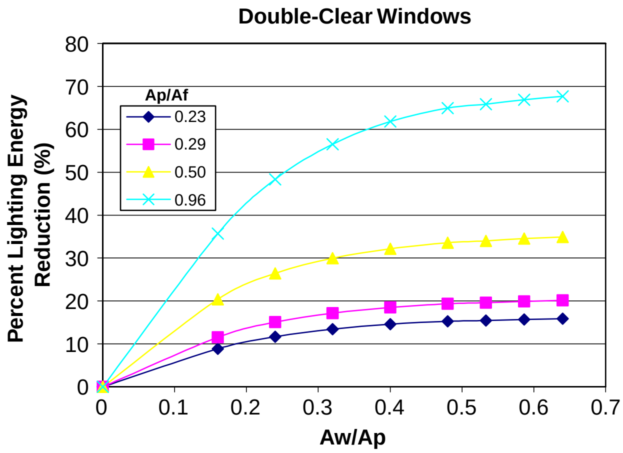

Fig. 3. Energy savings relative to window area for clear windows.

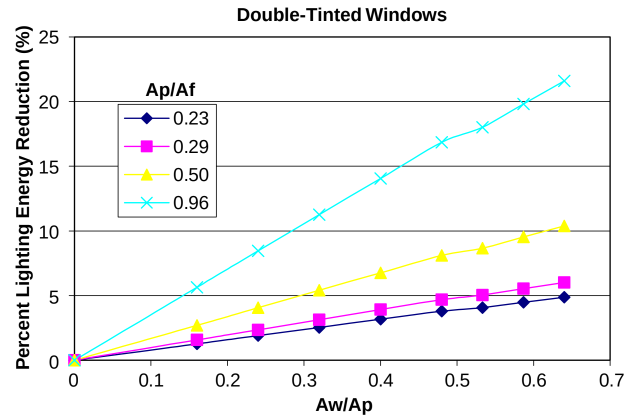

Fig. 6. Energy savings relative to window area for tinted windows in Atlanta, GA.

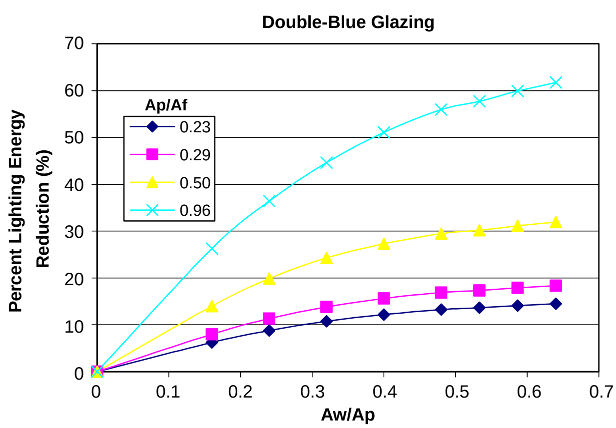

Fig. 4. Energy savings relative to window area for blue glazing.

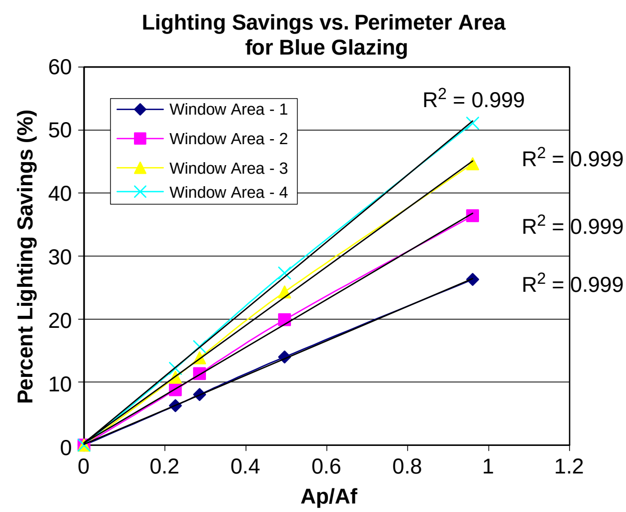

Fig. 7. Energy savings as a function of perimeter area.

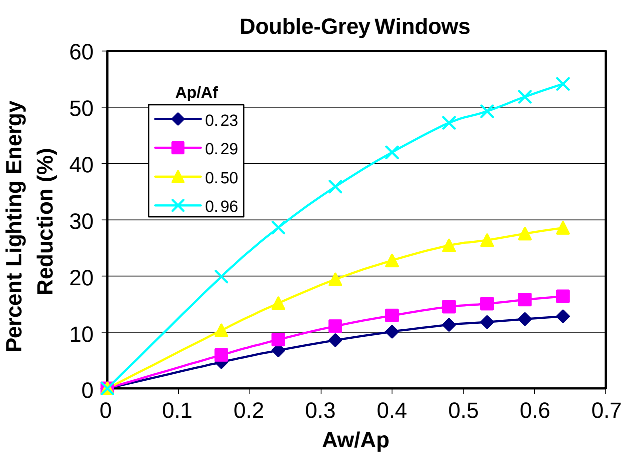

Fig. 5. Energy savings relative to window area for gray windows.

4.3. Perimeter to floor area

The simulation results showed that the perimeter to floor area is directly related to the potential lighting energy reduction of daylighting. For all cases, an increase in the A_p/A_f ratio resulted in an increase in lighting energy reduction. Analysis showed that the relative energy savings for different A_w/A_p ratios are directly proportional to change in the perimeter to total floor area, A_p/A_f, ratios. The percent change in energy reductions are plotted versus the A_p/A_f ratio for different window areas, and are shown in Fig. 7. It is clear that the perimeter area affects simply the magnitude of potential lighting energy savings in a linear fashion.

5. Development of a simplified analysis method

From the results of the parametric analysis presented above, it is apparent that there is a strong interdependency between the various parameters. Transmittance and A_w/A_p both impact the potential for light to enter into the individual spaces whereas the A_p/A_f ratio indicates the extent of the perimeter space that can be daylit, and likewise the magnitude of the lighting energy reduction. The overall savings are a function of all of these parameters.

Evaluating the combined parameter of transmittance and A_p/A_f, or daylighting potential, yields a consistent and predictable trend percent lighting reduction in the space. Fig. 8 demonstrates this relationship for building perimeter to total floor area ratios, A_p/A_f, of 0.23 and 0.96.

The trends shown in Fig. 8 further demonstrate that the transmittance and the window area have a similar effect on lighting energy reduction. The product (transmittance $^*A_w/A_p$) is often used as an indicator of the daylighting aperture [3,5]. The maximum potential limit of the lighting energy savings is obtained for high values of daylighting aperture as shown in Fig. 8. The maximum percent lighting reduction ranges from 16% to 68% for perimeter to total floor area, A_p/A_f, ratios of 0.23 and 0.96, respectively. The perimeter area acts like a multiplier, affecting the magnitude of energy savings. A comparison of the different building geometries, over a wide range of daylighting aperture values is shown in Fig. 9.

Due to the linear relationship between perimeter area and lighting energy savings (refer to the results shown in Fig. 7), lighting energy savings per the normalized perimeter area (i.e., A_p/A_f) can be evaluated as indicated in Fig. 10 for Atlanta, GA. The results of Fig. 10 clearly demonstrate that the lighting energy reduction per perimeter to total floor area ratio depends only on the daylighting aperture for all building geometries and all the glazing types.

A curve was fit to the data in order to obtain a general equation for the relationship between the energy savings and the daylighting aperture. The best curve fit was found to be of the form

$$y = b(1 - e^{-ax}), \tag{1}$$

where

$$y = \frac{f_d}{A_p/A_f} \quad \text{and} \quad x = \tau_w.(A_w/A_p),$$

with τ_w is the glazing visible transmittance of the window, a and b are correlations coefficients for which a physical meaning is provided in the following section.

The correlation coefficients a and b for Eq. (1) were determined for each geographical location, and are

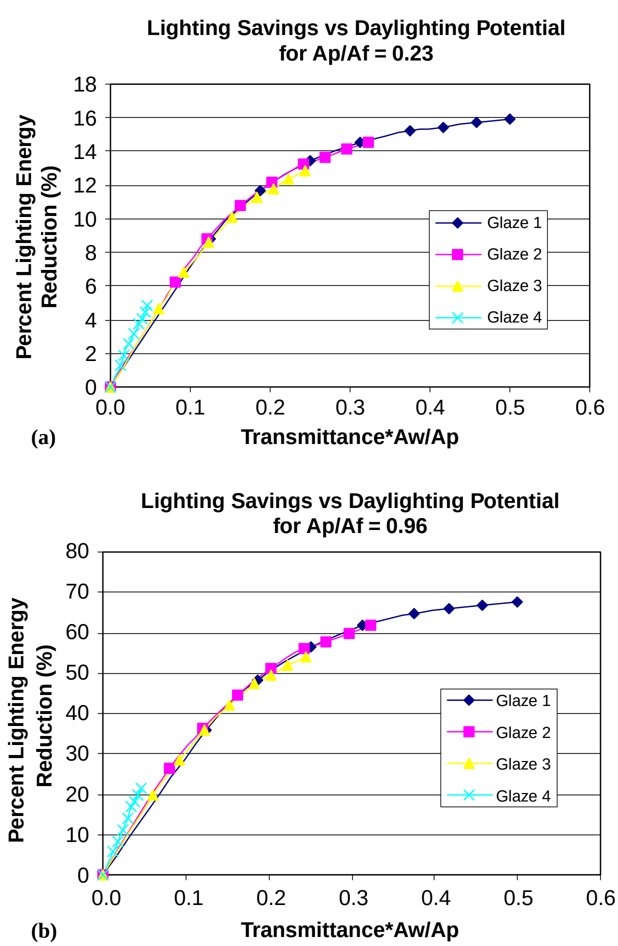

Fig. 8. Energy savings as a function of transmittance and window area for (a) $A_p/A_f = 0.23$ and (b) $A_p/A_f = 0.96$.

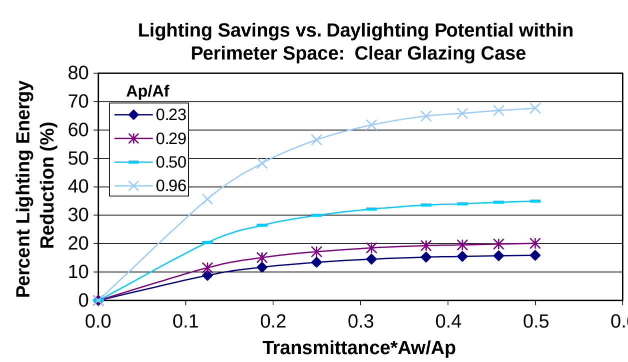

Fig. 9. Energy savings as a function of perimeter area.

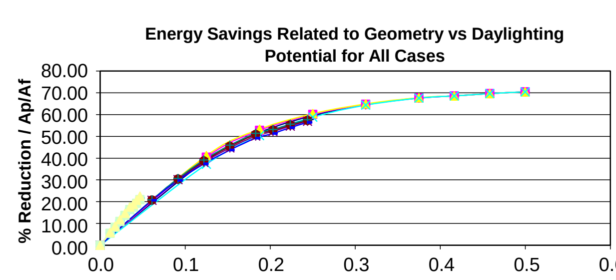

Fig. 10. Energy savings as a function of perimeter area for all geometries and glazing types, Atlanta, GA.

Table 2
Correlation coefficients for the lighting reduction curve Eq. (1)

	Coefficients	
	a	*b*
Atlanta	6	72
Chicago	6	69
Denver	7	73
Phoenix	8	75

summarized in Table 2. The curve-fit results are shown graphically for all locations in Fig. 11.

All locations displayed similar patterns. Cities with sunnier climates showed larger increases of energy reduction at low transmittance-window area values. This corresponds to a higher value for the coefficient *a* of 7.6 and 6.6 for Phoenix and Denver, respectively. In addition these locations had greater daylight savings potential at high transmittance $^*A_w/A_p$ values, which correspond to higher values for the coefficient *b*. It should be noted that there is no wide variations in the values of both *a* and *b* between the locations considered in this analysis.

Thus, to determine the percent savings, f_d, in annual use of artificial lighting due to implementing daylighting using dimming controls in office buildings, the following equation can be used:

$$f_d = b[1 - \exp(-a\tau_w A_w/A_p)]\frac{A_p}{A_f}, \tag{2}$$

where the coefficients *a* and *b* are provided in Table 2 for selected locations. For other geographical sites, the coefficients *a* and *b* can be determined using the same procedure presented in this paper.

6. Physical interpretation of correlation coefficients

To understand the physical meaning of the coefficients *a* and *b*, a simplified model for calculating illuminance in a daylit space is considered. The model is based on the daylight factor technique which related the average indoor daylight illuminance to the outdoor illuminance on a vertical surface (i.e., a window) using average sky conditions [12].

When the window area and/or glazing transmittance are small enough so that natural light can always be used beneficially to illuminate the space, the annual average light flux entering the space through the window, in Φ_{in}, can be estimated from the annual average vertical outdoor illuminance, $E_{v,out}$, as follows:

$$\Phi_{in} = E_{v,out}\tau_w A_w. \tag{3}$$

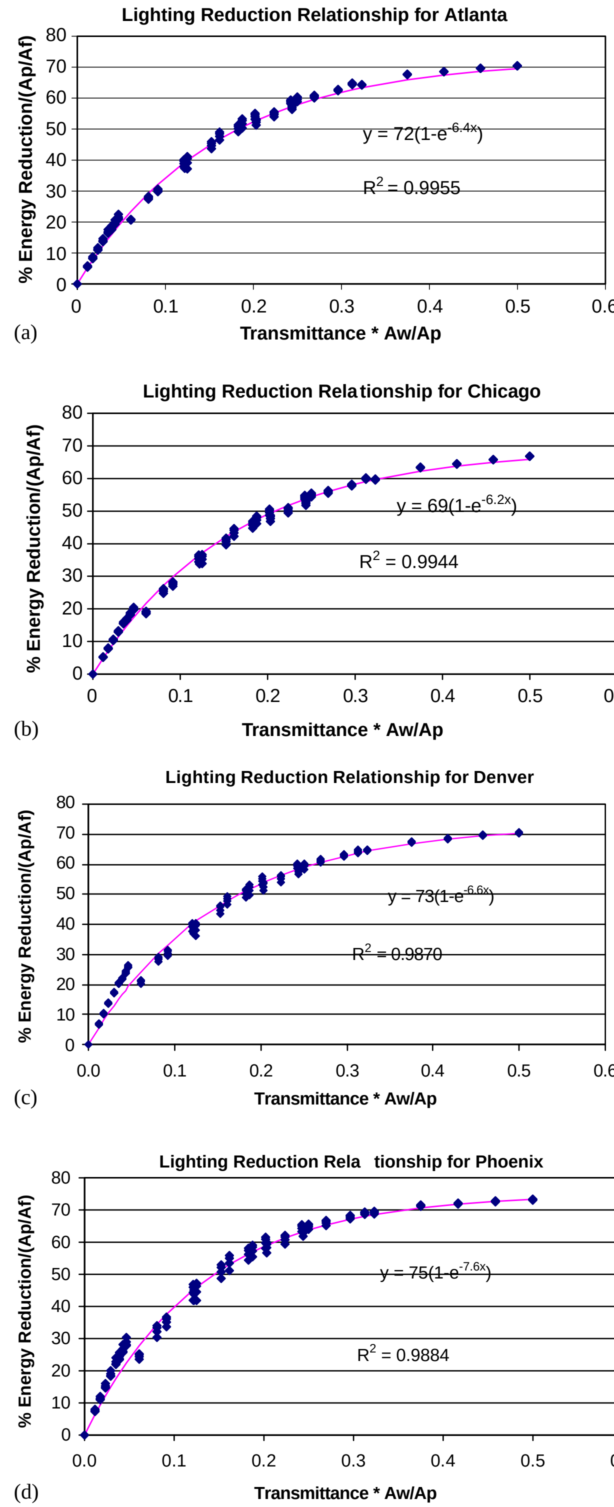

Fig. 11. Lighting reduction correlations for four US locations. (a) Atlanta, GA, (b) Chicago, IL, (c) Denver, CO, (d) Phoenix, AZ.

The annual average entering light flux per unit floor area, E_{in}, is then

$$E_{in} = \frac{\Phi_{in}}{A_f} = E_{v,out}\tau_w\frac{A_w}{A_f}. \tag{4}$$

The percent energy savings from reducing the annual use of artificial lighting, f_d, to maintain an illuminance set-point, E_{set} [i.e., 50 fc (500 lx) in this study] is proportional to the relative contribution of daylighting, that is

$$f_d = k.\frac{E_{in}}{E_{set}}, \tag{5}$$

where the constant k depends on the daylighting controls (for automatic dimming controls, k is typically equal to unity).

Therefore, combining Eqs. (4) and (5):

$$f_d = k.\frac{E_{v,out}}{E_{set}}\left(\tau_w \frac{A_w}{A_f}\right). \tag{6}$$

When the window area is small (that is $x \ll 1$), the expression of Eq. (1) can be approximated as follows:

$$\frac{f_d}{A_p/A_f} = abx = ab\left(\tau_w \frac{A_w}{A_p}\right). \tag{7}$$

Or

$$f_d = ab\left(\tau_w \frac{A_w}{A_f}\right). \tag{8}$$

By comparing Eqs. (6) and (8), it is apparent the product of the two coefficients a and b can be estimated from readily available data including the annual average outdoor illuminance level on vertical surfaces, $E_{v,out}$, the illuminance set-point, E_{set}, and a daylighting control parameter, k:

$$ab = k.\frac{E_{v,out}}{E_{set}}. \tag{9}$$

The coefficient b represents the percent of lighting reduction when the daylighting aperture, x, is large (i.e., $y \to b$ when $x \to \infty$). Thus, the coefficient b represents the percent of time in a year that daylighting illuminance level can provide the required design illuminance set-point, E_{set}. In other terms, the coefficient b measures the daylighting availability during building operating hours in a given geographical location.

In summary, both coefficients a and b can be estimated based on the outdoor illuminance level (using, for instance, a frequency distribution for outdoor illuminance levels), the desired illuminance set-point, and the daylighting controls.

7. Verification and validation analyses

7.1. Verification analysis

A verification of the developed calculation method has been carried out using new building configurations not used in developing the correlation coefficients of Eq. (1). To verify the accuracy of the developed simplified model, its predictions have been compared with results obtained from DOE-2 simulations for a 400 ft × 100 ft (122 m × 30.5 m) building with A_p/A_f ratio of 0.29. Tables 3 and 4 compare results from the simplified method and the simulation program for blue glazing with a daylighting aperture (i.e., x = transmittance$^*A_w/A_p$) of 0.182 and gray glazing with a daylighting aperture of 0.137, respectively. For all locations and building configurations, the simplified method predictions agree well with the simulation tool results.

Table 3
Difference between daylight savings estimated from the simplified method and from detailed simulation tool for blue glass

	Percent savings		
Location	Simulation	Simplified method	Difference
Atlanta	14.80	14.36	0.45
Chicago	13.54	13.53	0.02
Denver	14.93	14.79	0.14
Phoenix	16.63	16.29	0.34

Table 4
Difference between daylight savings estimated from the simplified method and from detailed simulation tool for gray glass

	Percent savings		
Location	Simulation	Simplified method	Difference
Atlanta	12.05	12.20	−0.15
Chicago	10.95	11.46	−0.51
Denver	12.15	12.61	−0.46
Phoenix	13.95	14.08	−0.13

7.2. Validation analysis

Predictions from the simplified method have been compared against recently reported experimental test data obtained for an office space located in Istanbul, Turkey [13]. The office space is 20.5 ft (6.25 m) long, 11.0 ft (3.35 m) wide, and 10.70 ft (3.25 m) high with clear glazed windows having a total area of A_w = 32.60 ft^2 (3.03 m^2) and a visible transmittance of τ_w = 0.78. The office is occupied from 8:00 am to 6:00 pm. The performance of a daylighting dimming control system has been monitored for 1 year to maintain an illuminance level of 50 fc (500 lx) on a working desk. The experimental data have indicated that the daylighting saves 31% of the total annual energy use from the artificial lighting system.

To obtain results from the simplified method presented in this paper, the coefficients a and b for Eqs. (1) and (2) found for Denver, CO are used since Istanbul has a latitude of 40°38′ (Denver's latitude is 39°75′) and

Table 5
Calculation of the percent savings, f_d, based on Eq. (2) for an office space in Istanbul

Parameter	Value	Comments
Perimeter to total floor ratio A_p/A_f	0.59	$A_p = 3.35\,m \times 3.7\,m = 12.40\,m^2$ $A_f = 3.35\,m \times 6.25\,m = 20.94\,m^2$
Daylighting aperture $\tau_w A_w/A_p$	0.19	$\tau_w = 0.78$; $A_w = 3.03\,m^2$
Simplified method prediction for f_d in percent	31.7	Eq. (2) with $a = 7$ and $b = 73$
Experimental data results for f_d in percent	31.0	Based on experimental data [13]

more than 62% (compared to 70% for Denver) of days in 1 year are sunny and clear. Table 5 summarizes the various parameters used to estimate the percent savings, f_d, in annual energy use of artificial lighting due to daylighting based on Eq. (2).

As illustrated in Table 5, the proposed method agrees well with experimental measurements of the energy savings of artificial lighting electricity use obtained from daylighting dimming control system.

8. Conclusions

The effects on artificial lighting savings of building geometry, window area, window type, and perimeter area for four US locations have been analyzed when daylighting is used. As expected, the daylighting aperture—defined as the product of window visible transmittance and window to perimeter floor area ratio—was found to have a significant impact on energy savings from daylighting. Increasing daylighting aperture (either by increasing glazing transmittance or window area) leads to greater daylighting benefits. It has been shown that a daylighting aperture greater than 0.3 will yield diminishing returns on energy savings. It has also been found that geographical location had relatively low impact on daylighting savings potential.

A simplified analysis method has been developed to estimate the potential for overall building lighting energy reduction from the window transmittance and window area. Physical insights have been presented to estimate the model coefficients for any geographical location. Building designers can use the proposed simplified method to quickly determine the potential lighting energy reduction from daylighting given window type, window area, and building geometry for typical office buildings.

Additional work is needed to further validate, refine, and expand the proposed method to deal with any building type and daylighting control strategy and possibly to predict the impact of daylighting on the overall building energy use.

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