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ANALYSIS OF ELECTRICAL ENERGY SAVINGS FROM DAYLIGHTING THROUGH SKYLIGHTS

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ABSTRACT

This paper provides a simplified analysis tool to assess the energy saving potential of daylighting for commercial buildings through skylights. Specifically, the impact of daylighting is investigated for various fenestration opening sizes, glazing types, control strategies, and geographic locations. A top floor of a prototypical office building has been considered in the analysis. The results obtained for the office building can be applied to other types of buildings such as retails stores, schools, and warehouses.

Based on the simulation analysis results, it was determined that skylight to floor ratio more than 0.3 does not affect significantly the lighting energy savings. An optimum value of skylight to floor area ratio was found to be 0.2 to minimize the annual total building energy use.

KEYWORDS: daylighting controls, electrical, lighting skylights

INTRODUCTION

Electrical lighting accounts for significant portion of total energy use in most commercial buildings. In the US, it is estimated that lighting accounts for up to 40% of total electricity used by commercial buildings [1]. In order to reduce energy used by lighting, several measures have been proposed such as the use of compact fluorescent lamps, installation of occupancy sensors, or implementation of better design strategies to minimize the number of fixtures. Though beneficial, these measures require the continuous use of artificial lighting to illuminate buildings.

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.

There are several techniques used to provide daylighting. The two main techniques suitable for commercial building include toplighting and sidelighting. Figure 1 gives an overview of commonly used toplighting configurations for commercial as well as residential buildings. Skylights and clerestories provide about three times the amount of daylight as vertical windows [5]. Since skylights can be placed closer to the center of an area, they provide more uniform lighting than sidelighting (i.e., windows). Diffusing glazing materials, sometimes in combination with ceiling louvers or lenses, can be used to control the brightness of direct sunlight. Total light transmission and toplight surface luminance can be balanced with glazing materials by selecting appropriate transmittance values.

Several studies have shown the benefits of daylighting through both skylighting and windows. However, simplified analysis tools to determine the energy savings potential from daylighting are rare especially for skylights. Krarti et al. [6] have developed a simplified method to estimate electrical lighting savings from daylighting through sidelighting systems. No similar method existing for toplighting systems.

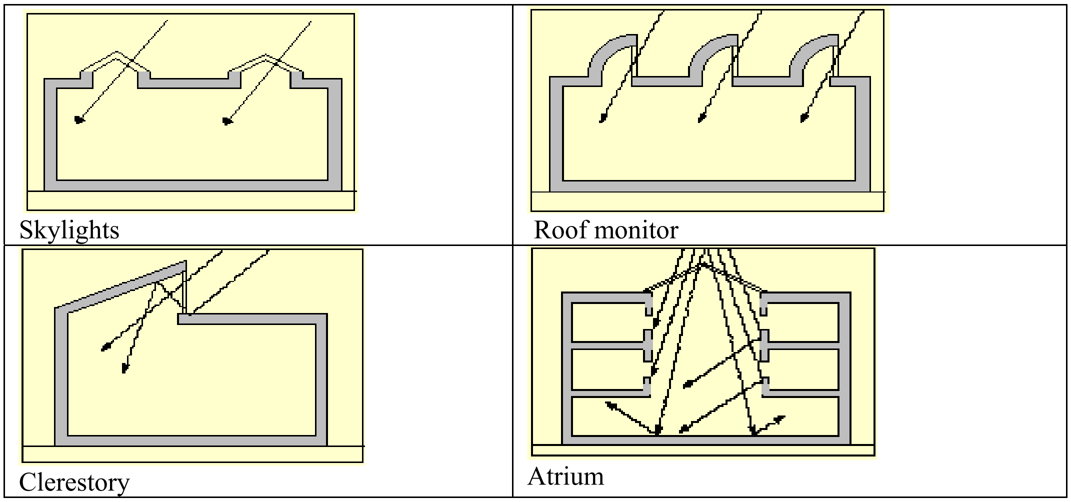

Figure 1: Common toplighting techniques used in buildings

This paper provides an extension of Krarti et al.'s method to skylights. In particular, the results from a series of simulation analyses are summarized and a simplified calculation method is developed to determine the effectiveness of daylighting in reducing electrical energy consumption in buildings through skylight fenestration. The energy savings from daylighting are investigated for various glazing types, skylight sizes, control strategies, and geographic locations.

BUILDING DESCRIPTION

Figure 2 illustrates a perspective view of the building model considered in the analysis. It is assumed that the building model represents the top floor of an office building. However, the model can represents other building types such as warehouses, schools, or retail stores with a similar lighting schedule considered in the analysis. The building model consists of 30 m x 30 m or 900 m^2 (9,690 ft^2) floor area. The height from the floor to the roof is 5 m (16.5 ft). The building is made up of brick walls and concrete roof. The floor is assumed to be adiabatic. The electric lighting is assumed to be operating from 8:00 am through 6:00 pm from Monday through Friday. During other periods (nights and weekends) only 5 percent of the lights are assumed to be on for security reasons. The lighting density for the office space is assumed to be 20 W/m^2 (2.0 W/ft^2).

The analysis has been carried out for several geographic locations including five sites in the US: (Denver, Washington, Chicago, Phoenix, and San Francisco) and eight other sites throughout the world covering Europe (Frankfurt, Rome, and Manchester), Africa (Cairo and Tunis), Asia (Islamabad and Riyadh), and South America (Mexico City).

A detailed building energy simulation tool, DOE-2.1E [7], is utilized to determine the impact of daylighting controls through skylight aperture on lighting electricity use as well as total electricity use for the prototypical building.

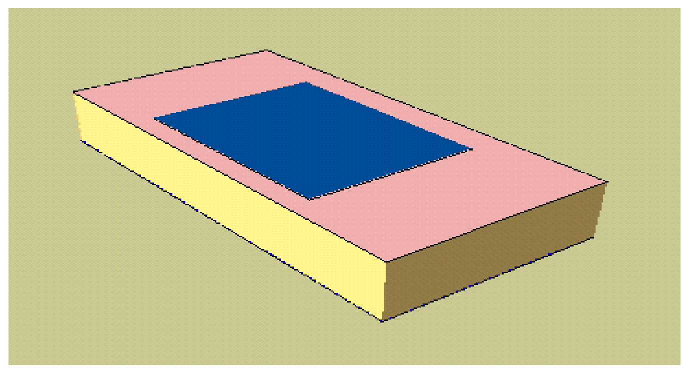

Figure 2: Building model considered in the analysis

To encompass the wide range of products currently available in the market, four glazing types with different visible transmittance and solar heat gain coefficient (SHGC) were selected and analyzed. Table 1 lists the window areas and glazing types used in the parametric analysis. Five US locations and selected international locations covering Europe, Africa, Asia and South America, were evaluated to determine the impact of a myriad of climatic conditions and latitudes on daylighting benefits.

The following parameters are defined throughout the analysis.

- A_f: total floor area of the building
- A_s: total skylight area

- τ_s : visible transmittance for the skylight glazing
- D: distance between two uniformly spaced skylights as illustrated in Figure 3.
- A: effective length of skylights as indicated in Figure 3.

Table 1: Glazing properties and range of Aw/Ap ratios used in the parametric analysis

Glazing Type	Number of Panes	Visible transmittance (τ_s)	Solar Heat Gain Coefficient (SHGC)	Skylight to floor area ratio (A_s/A_f)
Double clear	2	0.781	0.72	0.0-0.6
Double green	2	0.664	0.49	0.0-0.6
Double bronze	2	0.473	0.31	0.0-0.6
Single bronze	1	0.534	0.37	0.0-0.6

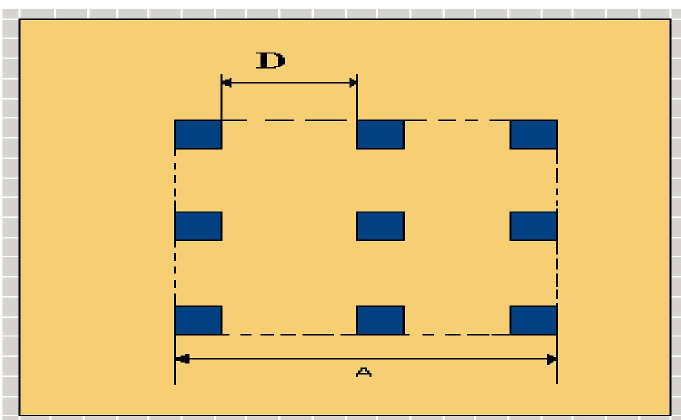

Figure 3: Distribution of skylights over the building roof

The following normalized parameters are defined to present the results:

- A_s/A_f: skylight to floor area. This parameter provides a good indicator of the skylight size relative to the floor area.
- d_a: normalized daylighting aperature area ($d_a = \tau_s A_s/A_f$)
- f_d: fraction of the annual total artificial lighting energy consumption saved through the use of daylighting from skylight.

IMPACT ON THE ELECTRICAL LIGHTING USE

Skylight Area to Perimeter Floor Area

The impact of skylight to floor area ratio, A_s/A_f, on lighting energy reduction when daylighting controls are implemented is investigated for various glazing types. As expected, it is found that an increase in the A_s/A_f ratio results in higher savings of lighting energy use for all skylight types and geographic locations. In addition, it is found that higher visible transmittance for skylight glazing leads to increased daylighting benefits and higher savings in electrical lighting use. Figure 4 illustrates the annual lighting energy savings as a function of the A_s/A_f ratio for a set of glazing types when the building is located in Tunis, Tunisia.

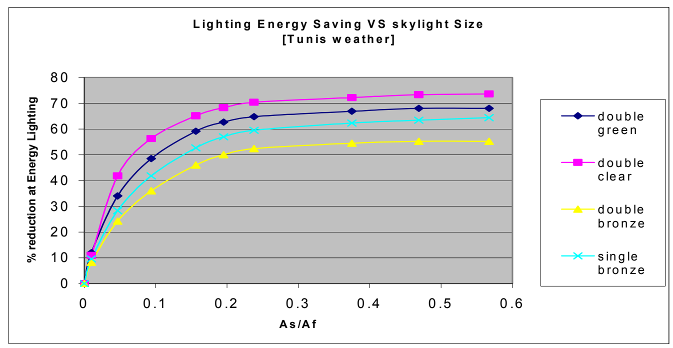

Figure 4: Impact of skylight opening on the electrical lighting energy in Tunis

By introducing a daylighting aperture (i.e., $d_a = \tau_s A_s/A_f$), the electrical lighting savings associated with daylighting can be expressed using a simplified correlation. Figure 5 illustrates this relationship for Tunis and for all the glazing types. In particular, the results show that increasing the daylighting aperture, by increasing either glazing visible transmittance and/or skylight to floor area ratio, above 0.2 does not provide significant additional lighting energy savings.

According to Figure 5, a simple relationship exists between the energy savings and the daylighting aperture. Similar to the method proposed by Krarti et al. [6], it is found that an exponential function could be used to determine the percent savings, f_d, in annual use of artificial lighting due to daylighting through skylights for all the locations considered in the analysis:

$$f_d = b[1 - \exp(-a d_a)] = b[1 - \exp(-a \tau_s A_s / A_f)] \quad \text{Eq. (1)}$$

Where:

The coefficient a and b are provided in Table 2 for the geographic locations considered in the analysis, when continuous dimming controls are utilized to maintain 500 lux (50 fc) in the work plane level (0.75 m or 2.5 ft). As discussed in [6], the coefficients a and b have some physical interpretation. In particular:

- The coefficient b represents the percent of time in a year that daylighting outdoor illuminance level can provide the required design indoor illuminance set-point, E_{set}. In other terms, the coefficient b measures the daylighting availability during building operating hours in a given geographical location.

- The product of the two coefficients *a* and *b, a*b,* represents the faction of outdoor daylighting illuminance that can be effectively utilized by the daylighting control system to meet the indoor illuminance level. The coefficient, a, depends mainly on the daylighting control strategy.

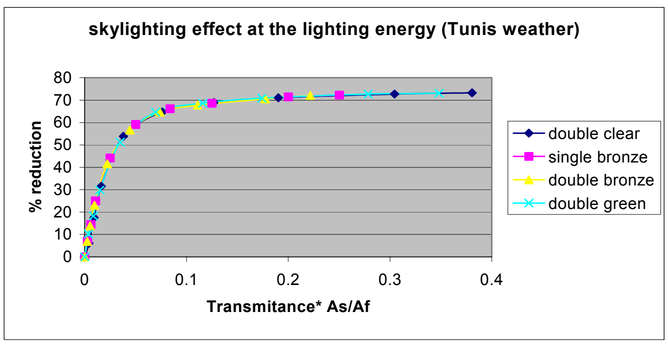

Figure 5: Impact of skylight opening aperture on the electrical lighting energy in Tunis.

Locations with sunnier climates showed larger increases of energy reduction at low transmittance-skylight area values. This corresponds to a higher value for the coefficient a. In addition these locations had greater daylight savings potential at high skylight daylighting aperture, d_a values which correspond to higher values for the coefficient b.

Table 2: Correlation coefficients a and b for the lighting reduction equation, Eq.(1)

Location	Coefficients for Eq. (1)	
	a	b
Washington	17.2	68.7
Chicago	16.2	69.5
Phoenix	20.6	73.2
Denver	18.1	70.4
San Francisco	19.1	71.2
Mexico City	24.5	70.5
Tunis	23.7	72.5
Cairo	23.6	71.3
Riyadh	20.3	70.7
Islamabad	21.2	69.8
Roma	16.4	71.2
Frankfurt	13.5	68.7
Manchester	16.3	67.3

Daylighting Control Strategy

Two types of daylighting controls are generally utilized to reduce electrical use in buildings including:

(a) Continuous dimming controls that vary the light output of the lighting fixtures linearly with the electrical input power as shown in Figure 6(a) The fractional light output decrease from 1.0 at full power to a value $F_{L,Min}$ at a minimum power faction $F_{P,Min}$. The lower values of the fractions $F_{L,Min}$ and $F_{P,Min}$, the more savings would be achieved by daylighting.

(b) Stepped controls that vary both power input and light output of the lighting fixtures in discrete and equally spaced steps as indicated in Figure 6(b).

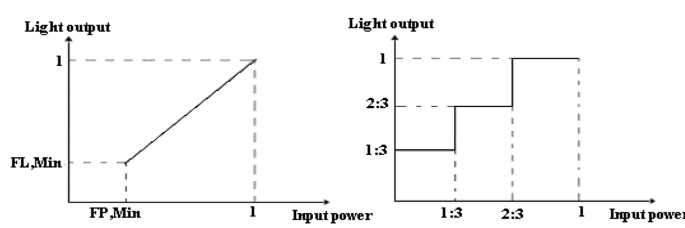

Figure 6: Typical daylighting controls, (a) Dimming Control, (b) Stepped Control

Table 3 lists the coefficients a and b for various dimming and stepped control strategies for the geographic locations considered in this analysis. The coefficients a and b are obtained from a series of simulation analysis using the prototypical building model of Figure 1. As expected, the control strategy has a significant effect on the performance of daylighting system as evident by the variation of the coefficient b, which provides an indication of the maximum possible savings of electrical lighting achievable by incorporating daylighting.

For stepped controls, the potential savings in lighting energy use increases with the number of steps. For the dimming controls, daylighting benefits are reduced when the minimum light output and power input fractions (i.e. $F_{L,Min}$ and $F_{P,Min}$) are increased. Dimming controls with low values for $F_{L,Min}$ and $F_{P,Min}$ achieve the highest reduction in electrical lighting for all the locations.

Impact of skylight distribution

In this section, the impact on the electrical energy savings due to daylighting of skylight distribution on top of the roof is evaluated. In particular, the variation of the lighting energy savings due to daylighting is determined as a function of the distance between skylights, D as illustrated in Figure 3. A normalized distance D/A is defined so that when D/A=0, the entire effective skylight area (of length A) in the roof is covered with skylights. As D/A increases, less skylights covers the effective area.

Figure 7 shows the normalized lighting energy savings (i.e. percent savings for a given D/A value divided by the percent savings when D/A=0) as a function of D/A when the building is located in Tunis. As the ratio D/A increases, the normalized savings decreases linearly independently of the glazing type. The same trend is found for all other geographic locations. Effectively, an increase in the distance D reduces the daylighting aperture and thus the potential lighting energy savings from daylighting through skylights.

Table 3: Coefficients for the lighting reduction correlation of Eq (1) with various control strategies

Daylighting Control	Stepped Controls				Dimming Controls					
	2 steps		5 steps		$F_{L,Min} = F_{P,Min} =$ 0.01		$F_{L,Min} = F_{P,Min} =$ 0.3		$F_{L,Min} = F_{P,Min} =$ 0.5	
Location	a	b	a	b	a	b	a	b	a	b
Washington	9.4	49.3	13.6	61.2	17.2	68.7	17.2	45.7	17.2	31.6
Chicago	8.9	50.1	12.8	62.1	16.2	69.5	16.2	46.5	16.2	32.5
Phoenix	11.1	53.8	16.1	65.7	20.6	73.2	20.6	50.2	20.6	36.4
Denver	9.8	51.2	14.2	63.2	18.1	70.4	18.1	47.4	18.1	33.2
San Francisco	10.3	51.5	15.1	63.7	19.1	71.2	19.1	48.2	19.1	34.1
Mexico City	13.1	51.2	19.1	63.2	24.5	70.5	24.5	47.5	24.5	33.5
Tunis	12.6	53.4	18.4	65.1	23.7	72.5	23.7	49.5	23.7	35.2
Cairo	12.3	51.7	18.3	63.9	23.6	71.3	23.6	48.3	23.6	34.4
Riyadh	10.9	51.4	15.9	63.3	20.3	70.7	20.3	47.6	20.3	33.7
Islamabad	11.4	50.4	16.6	62.4	21.2	69.8	21.2	46.5	21.2	32.5
Rome	9.1	51.7	13.1	63.7	16.4	71.2	16.4	48.2	16.4	34.1
Frankfurt	7.6	49.3	10.6	61.4	13.5	68.7	13.5	45.6	13.5	31.6
Manchester	8.9	47.9	12.9	60.1	16.3	67.3	16.3	44.2	16.3	30.2

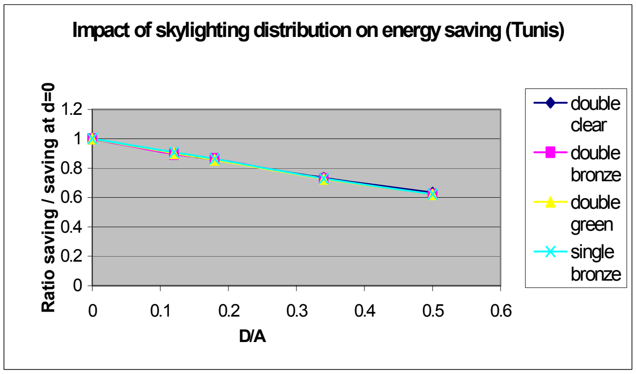

Figure 7: Impact of skylight distribution on the lighting energy savings

IMPACT ON TOTAL BUILDING LIGHTING USE

Skylights have two conflicting effects on building energy performance. In one hand, skylights can reduce the electrical lighting energy use through daylighting. In the other hand, the skylights tend to increase the building cooling loads since they receive significant solar gains especially during the middle of the day. Thus, if not properly designed, skylights can increase the cooling loads and thus the total building electrical use especially in hot climates. In this section, an optimum size of skylights is investigated for various glazing types and geographic locations. The optimum skylight size is determined so the annual total building energy use is minimum when daylighting is utilized.

Figure 8 illustrates the effects of skylight size to floor area ratio on the annual total electricity use of the prototypical building for Tunis weather conditions when no daylighting control is considered. As expected, an increase in the A_s/A_f ratio (i.e., skylight size) results in an increase of the annual total building electrical energy use for all glazing types. Since no daylighting control is utilized, an increase in the skylight area results in an increase in solar heat gains as well as in conduction gains through the roof and thus an increase in cooling load for the building.

When a daylighting control is installed, the annual total building electricity use exhibits minimal values for selected glazing types as illustrated in Figure 9 when the building is located in Tunis. In Figure 9, a dimming daylighting control with $F_{L,Min} = F_{P,Min} = 0.01$ is considered to control the electrical lighting system.

When skylighting glazing has high solar heat gain coefficient (SHGC) such as double clear glazing, the increased cooling load due to higher solar heat gains outweight any daylighting benefits of reduced electrical lighting energy use.

As indicated in Figure 9, the total electrical energy increases with the skylight area for double clear glazing. However, for tinted glazing with low SHGC values, there is an optimal value for the skylight area where the total electrical energy used by the building is minimal. For tinted glazing, the reduction in electrical lighting energy use due to daylighting can compensate the increase in cooling energy use due to the presence of skylights. For all the analyzed geographic locations, the optimal value for the skylight to floor area ratio is found to be $A_s/A_f = 0.2$ when green tinted glazing is utilized.

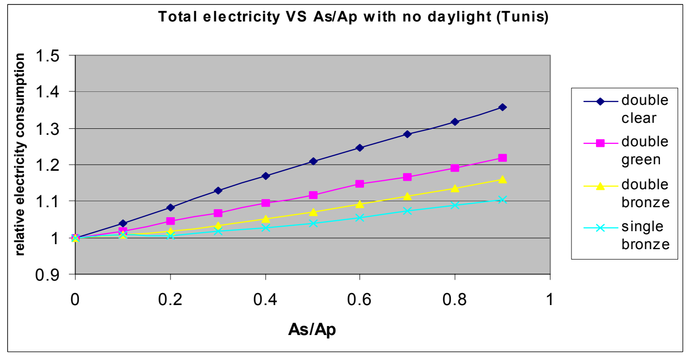

Figure 8: Effect of skylight size on the total annual electricity use with no daylight

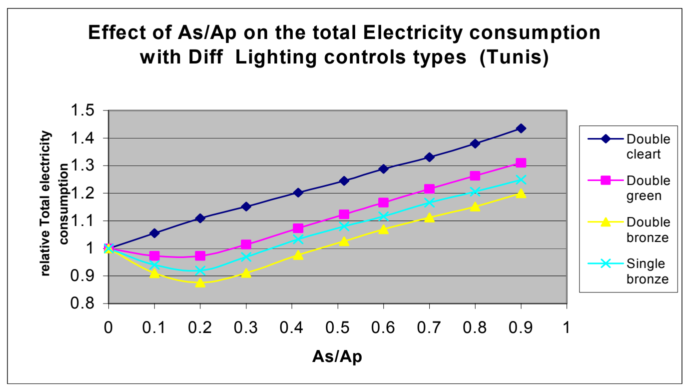

Figure 9: Effect of skylight to floor area ratio on the total annual electricity use in Tunis for various glazing types when dimming control of $F_{L,Min} = F_{P,Min} = 0.01$

SUMMARY AND CONCLUSIONS

A simplified calculation method has been developed through detailed simulation analysis to estimate the overall building lighting energy reduction due to daylighting from skylights. The simplified method can be utilized by architects and building designers to quickly determine the potential lighting energy reduction from daylighting given skylight type, skylight area, daylihting control strategy, and building geometry.

The impact of daylighting on the total building electricity usage has been also investigated for various glazing types for the skylights. For the geographic locations considered in the analysis presented in this paper, an optimal value of skylight to floor area ratio of 0.2 is found to minimize the annual total building electricity use for tinted glazing when daylighting dimming control is used.

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