СРПСКО ДРУШТВО ЗА ОСВЕТЉЕЊЕ
СРПСКИ КОМИТЕТ ЗА ОСВЕТЉЕЊЕ

SERBIAN LIGHTING SOCIETY
SERBIAN LIGHTING COMMITTEE

THE FIFTH CONFERENCE

BALKAN LIGHT 2012

PROCEEDINGS

October 03 – 06, 2012
Belgrade, Serbia

SESSION 7

PERFORMANCE EVALUATION OF AN AUTOMATICALLY CONTROLLED LIGHT SHELF

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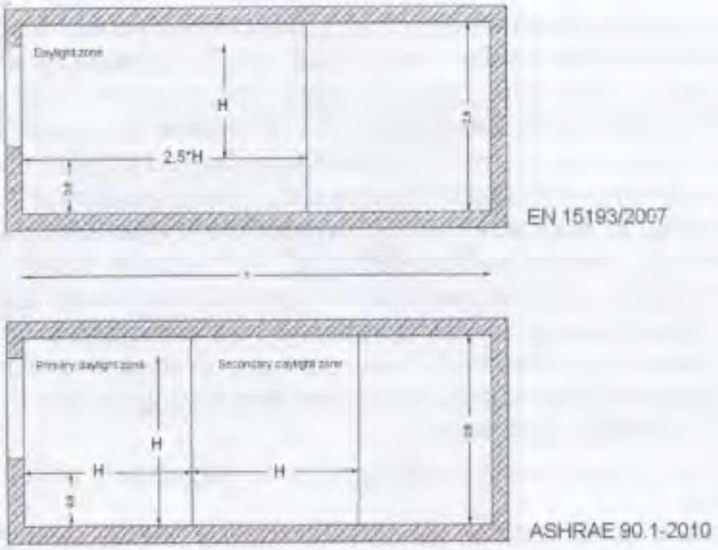
Abstract

Bringing glare-free daylight in the building core can significantly increase lighting energy savings. Over the years, various systems from Stationary Projecting Reflector Arrays to Anidolic systems have been proposed in an effort to increase the depth of the building's perimeter zone and enhance quality. The bibliography examining the effectiveness of static shelves in relation to geometric parameters (such as size, placement, ceiling height/inclination) and material properties (reflectance) is quite extensive, but it is extremely limited when automatic dynamic control is introduced. In sunny climates, a control strategy that will adjust the tilt angle of a lightshelf can be used to reflect sunlight to the ceiling, offering the ability to increase daylight levels in areas far away from the perimeter zone as defined in EN 15193, especially in cases when interior blinds are used to control glare. This paper presents a method of controlling tilt angle according to the position of the sun and a predefined target area on the ceiling and analyze lighting energy savings. The target used in this analysis is located beyond the border of the building's perimeter zone which equals 2.5 times the height difference between the window lintel and the reference plane. Two case studies were simulated in a typical south oriented office space a) with static and b) an automatically controlled exterior lightshelf. The space is separated into two lighting control zones and the difference in the performance (lighting energy savings) of these two systems is examined for Athens climatic data on an hourly basis.

1. Introduction

Exploitation of daylight can reduce considerably lighting energy consumption and peak electric loads as well. There are many studies presenting possible energy savings both via simulations and in reality especially in office buildings due to the use of a photosensor controlled lighting system. Literature [2,3,4] reports lighting energy savings up to 77%. It must be pointed out that in a number of cases these systems are not operating satisfactorily, [5] though the introduction of daylighting has additional benefits since it can mainly affect the occupants health and well being [6] and secondary their performance and productivity.

Although maximizing the areas benefiting from daylight can reduce the building's electric lighting consumption, solar heat gains/losses and glare issues should be balanced carefully. Many energy codes around the world propose a method for the determination of daylight zones close to façade apertures or below horizontal ones. In these zones, daylight harvesting control can be adopted. For example ASHRAE 90.1-2010 establishes primary and secondary daylight zones while EN 15193 [7] defines daylight zones in a slightly different way as presented in the following figure:



EN 15193/2007

ASHRAE 90.1-2010

Figure 1. Daylight zone definition according to EN 15193 and ASHRAE 90.1-2010.

The percentage of daylight zone in relation to gross floor area gives an indication of the possible lighting energy savings which is useful during the initial design stage. However some building energy rating/certification schemes like LEED [8] ask for a more detailed definition of daylight energy savings based either on a prescriptive method or simulation or in-situ measurements. Consequently, the challenge is to increase the size of these zones by bringing daylight to the building core.

Lightshelves can be used for this purpose , offering shading and sunlight redirection at the same time. Using a high reflectance ceiling, increased values of daylighting levels far away from the perimeter zone can be achieved, together with an improvement in uniformity. Over the years, various designs (exterior/ interior or both) have been proposed from Stationary Projecting Mirror Arrays [1] to anidolic ones [9] in an effort to supplant artificial lighting with glare free daylight (if possible).

In their simplest form lightshelves divide windows into two parts a lower-view window and a clerestory. The upper surface has a highly reflective finish either diffuse or specular and should not be seen by space occupants. Exterior lightshelves offer better shading while interior ones better glare protection. Tall windows favour their adoption which becomes problematic with lower ceiling height room configurations.

The importance of ceiling geometry has been examined by A. Freewan, L. Shao and S. Riffat [10] in an effort to improve uniformity and they concluded that the best ceiling shape was the one that is curved in the front and rear of the room.

Early studies [11] presented some practical advice on the dimensioning of static lightselves suggesting that the length of exterior shelves' can be up to 1.5 times the height of the clerestory window. Littlefair [12] combining measurements and simulation analysis concluded the lightshelves work best with a high ceiling (>3m) with depths roughly equal to the height of the clerestory for interior ones and no more than its distance from the working plane for the exterior. Overall, lightselves can perform best when there are external obstructions increasing core illuminance by 15%. Claros & Soler [13] measured light self performance as a function of its material properties and room reflectances. Mirrored shelves provided more than 750 lux from 8:00-18:00 for realistic interior reflectances in Madrid. Hu, Du and Place [14] explored the following parameters: light shelf length, ceiling height, and typical interior office configurations through measurements and simulations. Their conclusions were that lightshelf length should be optimized mainly according to the ceiling and daylight glazing height. Another parameter that can influence performance is the tilt of the lightshelf which can help to enhance sunlight penetration during the cooling period. Moore [15] suggests for south oriented shelves painted white, a tilt equal to 40^0 –(latitude/2) while Baker et al [16] using as design inputs the room depth to glass height above shelf ratio and the solar altitude proposed a graph giving the optimum tilt of lightselves under clear sky conditions. Reserach in relation to active/dynamic lightshelves is limited although during the year 1990 Place and Howard tested a sun tracking mirror self, increasing daylight to 14 m away from he window. According to Raphael B. [17] a possible explanation for this, is that these devices are treated as "passive design elements". In the same paper a lightshelf has been examined, with a rotating external part and an internal part that can be moved horizontally, producing a net energy saving of 12% compared to a static shelf. During the year 2007, Irving Montanar Franco [18] presented measurements in scale models equipped with static and dynamic light shelves. The conclusions were that heat gain was the same both in the passive and the automated shelf system.

2. Evaluation study

To test the influence of a suntracking lightshelf in lighting energy savings a 7m depth office space has been simulated with south oriented façade. Window is divided into two parts by a combination of an external specular sun-tracking lightshelf together with a diffuse internal in an effort to reduce glare. Office space characteristics are presented in the following table.

Dimensions (internal)	4 x 7 x 2.8 m
View Window	3.5 x 1 m (window sill 1m)
Clerestory window	3.5 x 0.5 m
Floor v. reflectance	0.3 (diffuse)
Walls v. reflectance	0.6 (diffuse)
Ceiling v. reflectance	0.8 (diffuse)
Lightshelf exterior v. reflectance	Total reflectance 95% Diffuse reflectance 12 %
Lightshelf interior v. reflectance	0.8 (diffuse)
Glazing v. transmittance	0.6 (normal)

Table 1. Ofice room characteristics

System operation is based on the rotation of the external lightshelf according to the sun's position and aiming point on the ceiling . It is evident that sunlight should be redirected away from the daylight zone to achieve electric lighting savings in areas further away from this zone. The tilt angle of the light shelf is defined according to the projected sun's elevation angle on the facade . Figure.. below presents the relation between the sun's position and aiming point .

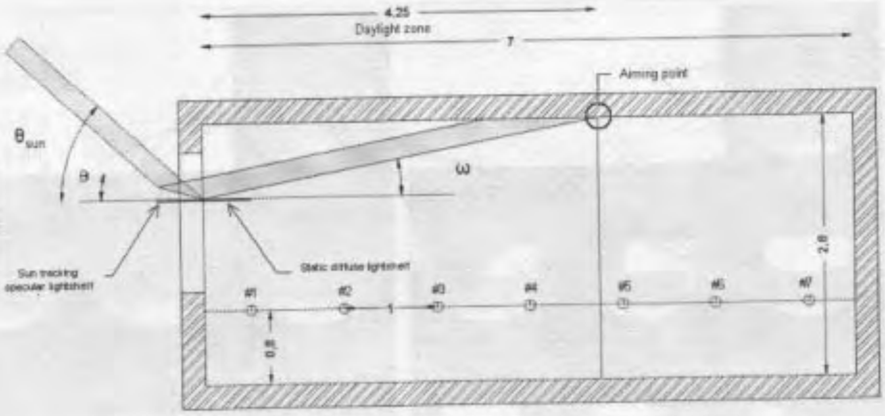


Figure 2. Definition of various angles and presentation of calculation points.

Using the above figure, the tilting angle of the lightshelf is defined as follows:

$$\theta=(\theta_{sun}-\omega)/2 \qquad (1)$$

where θ_{sun} is the projected sun's elevation angle and ω is a constant angle defined by the aiming point.

The graphs below present the tilting angle for winter and solar solstice for Athens , Greece geographical location and aiming point at 4.25 from the facade.

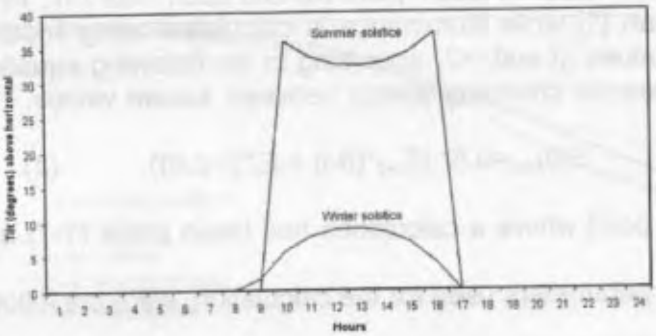
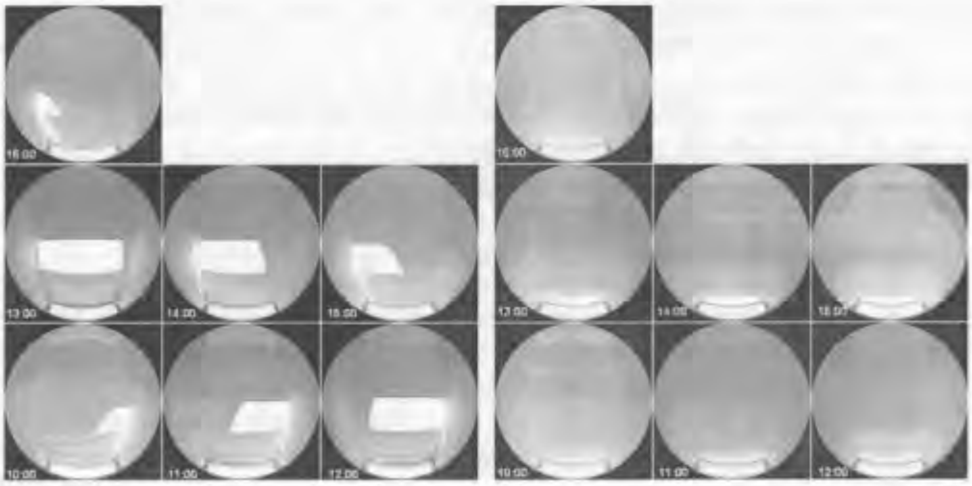


Figure 3. Lightself tilt angle during winter and summer solstice

Figure 4 presents synthetic images with sun patches on the ceiling when a tracking lightshelf is used.



Sun Tracking lightself

Horizontal static lightself

Figure 4. Synthetic hemispherical images of the room with sun patches distribution for two cases a) suntracking shelf and b) static

Calculation of interior daylight levels was performed using DAYSIM [19]. DAYSIM uses daylight coefficients approach in an effort to speed up the hourly calculation for a typical meteorological year. This procedure, though, has an additional problem with sun tracking lightshelves. Since there is a sun position change every time step, the tilt angle of the lighshelf should be adjusted accordingly. As a result the whole calculation should be repeated all over again. The solution to that problem was a series of hourly simulations from 0^0 to 44^0 with 2^0 step. Thus, for each point (n) and each hour (h) , tilt angle (θ) is estimated according to equation [1] while illuminance is calculated using linear interpolation between adjacent tilt angle values (i and i+2) according to the following equation considering that the illuminance values are not changing quickly between known values.

$$E(\theta)_{n,h}=0.5^* \left(E_{i+2}^*(\theta-i) + E_i^*(i+2-\theta)\right) \qquad (2)$$

Where n, h are the point where a calculation has taken place (1-7) and the hour of the day accordingly.

The main Radiance parameters used for the calculation were the following :

(ambient bounces) ab→ 7, (ambient division) ad→ 3000, (ambient accuracy) aa→0.1, (ambient resolution) ar→ 300, (direct relays) dr→1

3. Results

Three cases have been examined with the aiming point of reflected sun beam to be at 4.25 m, 5.62 m and 7m from the façade. When there is no sunlight on the façade, the lightshelf is positioned horizontally. Using only the clerestory window above the light shelf (6.2% WFR) as daylight provider , daylight autonomy (DA) values have been calculated across the measurement points. DA at a point represents the percentage of occupied hours on yearly basis during which illuminance values are greater than a predefined threshold, which in our case is 500 lux. Figure 5 presents DA versus distance from the facade

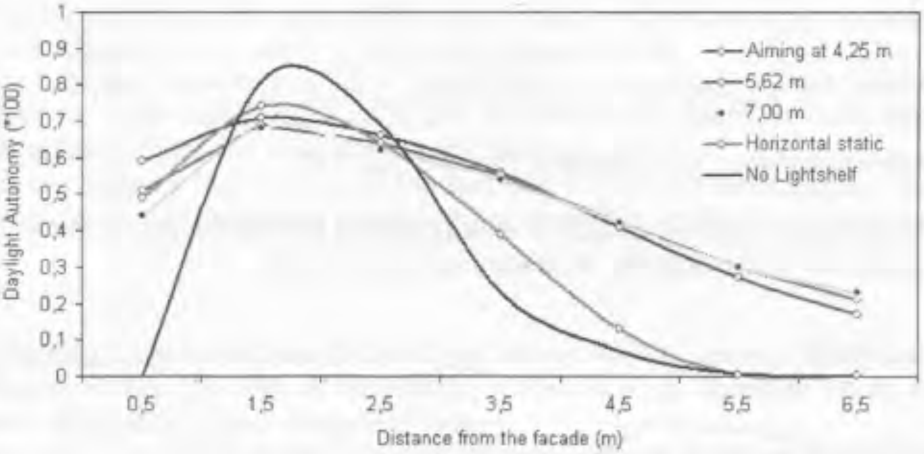


Figure 5. Daylight autonomy (scale 0-1) for all measurement points. Only clerestory window used in calculation.

In daylight zone (points 1-4) relative difference between DA values are at maximum 11.5% between sun tracking and static shelves. However rather large differences are observed in the rest of the room, from 525% when the aiming point is at 4.25m to a maximum 598% when the aiming point is at 7 m. These are due to the fact that a horizontal static shelf does not contribute a lot to daylight in areas far away from the façade.

Introducing a lower view window in the calculation seem to even DA differences between sun tracking and static shelves since more daylight enters the space. The results are presented in the figure below.

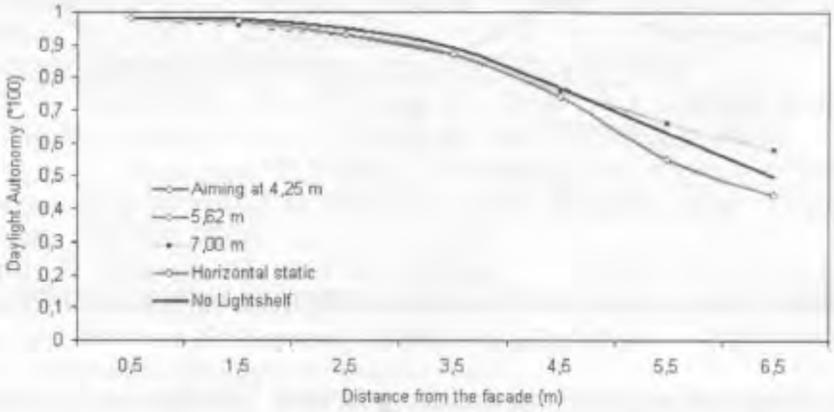


Figure 6. Daylight aytonomy (scale 0-1) for all measurement points. All façade windows used in the calculation.

Obviously the increase in illuminace values at the non-daylight zone improve uniformity.

Using EnergyPlus ideal continuous dimming system, lighting energy savings can be calculated for both daylight and non-daylight zones of the room.

There is a linear relationship between fractional input power f_P and fractional lighting output f_L. The latter is calculated according to the relationship:

$$f_L=\max[0, (500-\text{Daylight levels at a point})/500] \quad (3)$$

When the minimum lighting output is achieved (f_{Lmin}), there is a minimum power input f_{Pmin}. Both values depend on the type of the ballast. The relation between power f_P and f_L is :

$$\text{If } f_L<f_{Lmin} \rightarrow f_P=f_{Pmin}$$
$$\text{If } f_{Lmin}<=f_L<=f_L \rightarrow f_P=(f_L+(1-f_L)*f_{Pmin}-f_{Lmin})/(1-f_{Lmin}) \qquad (4)$$

For the present calculation f_{Pmin} equals 0.15 while f_{Lmin} 0.05.

In the following figure monthly results of energy saving for the daylight and the non-daylight zone are presented when only the clerestory window is used.

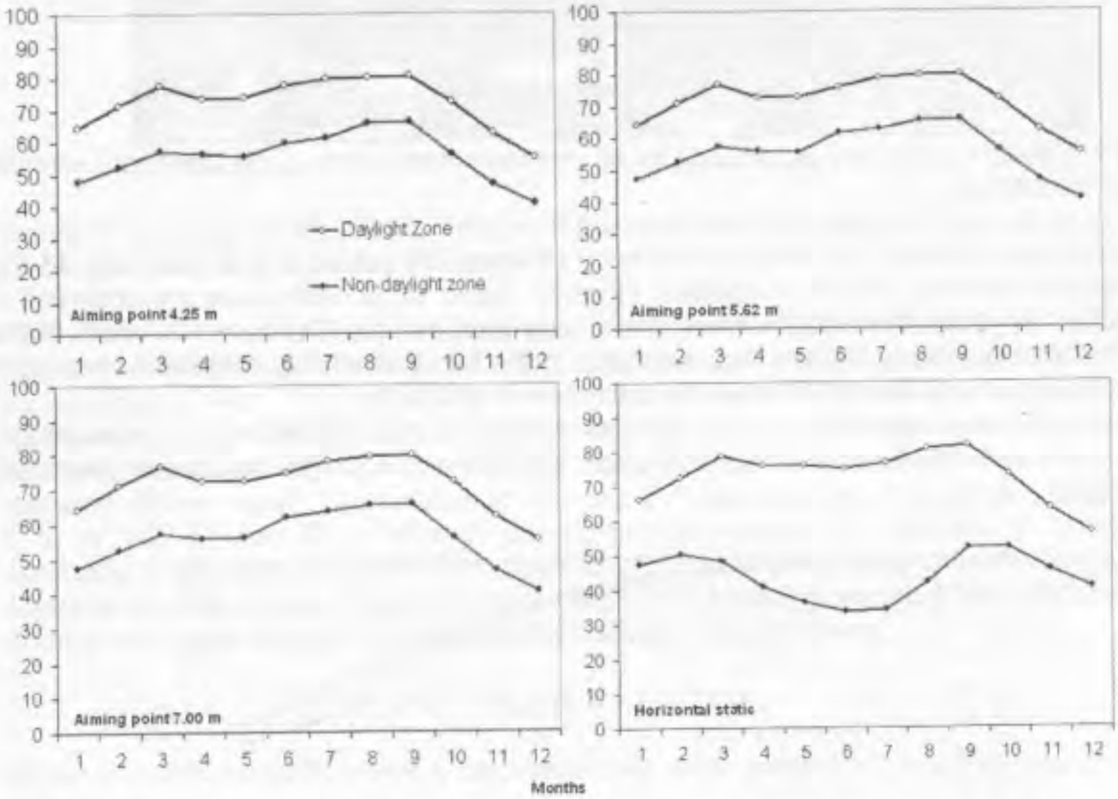


Figure 7. Monthly energy savings for the three sun tracking shelves and the horizontal static one.

Using a suntracking shelf and only the clerestory window , the non-daylight zone can achieve 21% more lighting energy saving , irrelevant of the aiming point.

4. Conclusions

Sun tracking lightselves can contribute to the increase of daylight levels in areas away from daylight zones increasing lighting energy savings and improving uniformity. The present study was limited to south windows only and an exterior sun tracking lightshelf. The findings of the comparison between sun-tracking shelves and static ones demonstrate that :

- Moving the aiming point to the back of the room does not have any important impact on Daylight Autonomy value as long as the aiming point is in the non-daylight zone.
- Daylight Autonomy values strongly depend on window size. Using only the clerestory window (6.2 % WFR) can increase DA in non-daylight area by more than 500% while when view window is used this difference reduced to 15%.

- Using a coninuous dimming system can increase lighting energy savings by 21% in the non-daylight zone using only the clerestory window.

Proper design of the clerestory window is crucial in achieving the best balance between daylight increase in the non-daylight zone and control of solar gains. A more detailed model for calculating solar gains due to inclined lightshelves is needed.

In reality some problems might arise, by the fact that if there are reflected sun beams on the ceiling located sensor of the lighting control system possible energy saving can deteriorate.

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This research has been co-financed by the European Union (European Social Fund – ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) - Research Funding Program: Heracleitus II. Investing in knowledge society through the European Social Fund.