Lighting energy savings due to the use of a sun tracking mirrored lightself in office buildings

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The proper use of daylight lays a solid cornerstone to the framework of energy saving techniques in non residential buildings, satisfying the occupants' physiological and psychological needs. It is directly connected with lighting, and if solar gains and glare issues are balanced carefully, with cooling energy savings as well especially in warm climates.

Mirrored 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. Since 1994, several variants have been proposed from Stationary Projecting Reflector Arrays to anidolic ones. Nevertheless, the majority of the systems examined in the literature are static while the analysis of their dynamic behavior is quite limited.

The paper examines a fenestration system which consists of a combination of an exterior suntracking mirrored lightshelf and a static diffuse internal one. Exterior lightself tilt angle is calculated according to the sun's projected elevation angle and the position of a predefined target area on the ceiling. Using this approach, lighting energy savings can be increased due to the increase in daylight levels in areas far away from the perimeter zone. Five case studies representing two typical south oriented office rooms with different depths and various Window to Floor ratios have been used. The results indicate that a suntracking lightself can increase considerably daylighting levels in areas away of the perimeter zone especially if a small window area is used.

1. INTRODUCTION

The practice of utilizing daylight represents a crucial requirement during the design process, but to guarantee a well-lit environment the amount and distribution of natural light that enters the space should have to be analysed in detail. A key aspect is to understand the dynamic nature of daylight and translate it in a manner that responds to the occupant's visual and perceptual needs, while at the same time taking into account its significant energy saving potential. Balancing antagonistic phenomena (control of solar gains-daylight adequacy) is what complicates the design process, not to mention the balance between energy conservation and occupants comfort, health and productivity. The exploitation of daylight can considerably reduce not only electric lighting energy consumption but peak electric loads as well. This can be achieved by increasing the perimeter area of the building (if sidelighting is used), an area which benefits most by daylight.

In sunny climates, with increased daylight availability, this maximization of perimeter areas has to be [1]accompanied by measures regulating the excessive heat and direct

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sun penetration. According to EN 15193-2007 [1], the perimeter area's depth is 2.5 times the difference between the height of the window lintel and the height of the working surface. A slightly different definition is used by the ASHRAE 90.1-2010.

Light shelves are often suggested in literature as an effective way not only to provide shade but also to improve the lighting quality of a space by redirecting light deeper into the space. Having the ability to act both as a shading device designed to block direct solar radiation before entering the interior space through the fenestration system and as a daylighting device when mounted at about mid-window height, sunlight bounces off the shelf and into the ceiling, pushing light deeper into the space, a light shelf can produce an improved daylight distribution at the back of a room, while the integration with lighting controls ensures that the use of electric lighting can be reduced.

The lightshelf can be either horizontal or inclined while it divides the window into two parts: a lower-view window and a clerestory one for provision of luminous flux .

Over the years, various designs (exterior/ interior or both) have been proposed from Stationary Projecting Mirror Arrays [3] to Anidolic [4]. Exterior light shelves act more efficient as shading devices by excluding direct solar radiation opposed to interior shelves which offer a glare-free environment with minimum occurrences and therefore less discomfort for the users.

The light shelf's geometrical (dimensions) and optical (surface reflectance) characteristics as well as the room dimensions; location; room surfaces reflectance; ceiling geometry and the window configuration itself are significant factors which affect the performance of the lightshelf and consequently, the overall performance of the space. The performance of light shelves has been addressed in several cases both as a shading device and as a daylighting system and has been compared against other shading devices [5, 12].

Claros and Soler [6] studied the dependence of lightshelf performance on solar geometry and surface reflectance. In the results, mirrored shelves provided more than 750 lux from 8:00-18:00 for realistic interior reflectances. Freewan [11] investigated the interaction between different lightshelf geometries combined with a curved ceiling and the analysis revealed that modifying lightshelf geometries will change the way that the light is collected and distributed. Also in another paper by Freewan et al. [12], the importance of the ceilings' geometry was examined in an effort to improve uniformity using an optimum ceiling shape. Beltran et al. [13] presented two daylighting systems that passively redirected the sunlight beam further from the window wall.

Design considerations in dimensioning of static lightshelves have been presented by Selkowitz et al. [14]. They suggested that the length of exterior shelves can be up to 1.5 times the height of the clerestory window. Other studies conducted by Littlefair [15] concluded that lightshelves perform more efficiently at high floor to ceiling heights- more than 3m- with depths roughly equal to the height of the clerestory for interior configurations and no more than its distance from the working plane for the exterior. Hu, Du and Place [16] assessed the performances of lightshelf systems in the context of various interior configurations via measurements and simulations: light shelf length, ceiling height, and typical interior office configurations. Joarder et al. [17] studied the height of the lightshelves to enhance daylighting quality. Six alternative scenarios were created with varying heights of lightshelves. The results showed that lightshelves at a height of 2m above floor level perform better among the other examined alternatives.

Apart from the length, height and position of the self another parameter is the tilt angle that can also influence the performance of the system and enhance sunlight penetration. Moore [18] suggested tilt angles "40^0- latitude/2" for South-oriented spaces with lightselves painted white while Baker et al [19], by taking into account the rooms depth via the glass height above the shelf and the solar altitude, found a ratio and proposed a graph which gave the optimum tilt of lightshelves under clear sky conditions.

But when it comes to dynamic approaches, like in the case of shading elements such as automated venetian blinds, the research is limited. Place and Howard [20] tested a sun tracking mirror self and results showed an increase in daylight up to 14m away from the window. According to Raphael B. [21] a possible explanation for this static treatment of lightshelves, is that these devices are handled more as passive elements rather than dynamic and in the same paper a lightshelf with a rotating external part and an internal part that moved horizontally, produced net energy savings of 12% compared to a static shelf. Another study conducted by Irving Montanar Franco [22] presented the finding of scale models equipped with static and dynamic lightshelves. The conclusions were that heat gains were the same both in the passive and the automated shelf systems.

Recently Kostantoglou et al. presented the influence of the clerestory window equipped with a suntracking lightshelf on daylighting levels [23]

2. METHODOLOGY AND RESULTS

As already mentioned , the main scope of the present paper is to investigate the behaviour of an exterior sun tracking lightshelf in terms of possible lighting energy savings. Two parameters affect lightshelf tilt a) the position of the sun and b) the aiming point at the ceiling. For the proposed control strategy, the projected sun's elevation (θ_{sun}) is used while the aiming point is equal to the room's depth as presented in the following figure.

Figure 1 . Representation of the characteristic angles of the system.

The lightshelf's tilt angle (θ_{ls}) is defined as follows:

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

when $\theta_{ls}<0$ then $\theta_{ls}=0$.

Two typical south-oriented office spaces with two depths -5m and 7m respectively- have been simulated. Window is divided into two parts by a combination of an external specular sun-tracking lightshelf with a diffuse internal in an effort to reduce direct sunlight on the working surface. Five cases in total have been examined as presented in the following table:

	Dimensions (width , depth, height) in m	Orientation	Window to floor ratio	Exterior Lightshelf Dimensions (width, length)	Interior Lightshelf Dimensions	Lightshelf height
Case 1	4x5x2.8	South	10%	1.33x 0.5	1.33x 1	2
Case 2	4x5x2.8	South	20%	2.66 x 0.5	2.66 x 1	2
Case 3	4x5x2.8	South	27.9%	3.73 x 0.5	3.73 x 1	2
Case 4	4x7x2.8	South	10%	1.86 x 0.5	1.86 x 1	2
Case 5	4x7x2.8	South	20%	3.73 x 0.5	3.73 x 1	2

Table 1. Geometrical description of the case used.

For all spaces a 0.5 m x 0.5 m measurement grid was selected. Based on the dimensions of the spaces as presented in the Table …. above, angle ω is equal to 9^0 for the small space and 6.5^0 for the large one.
For the calculation of interior daylight levels, DAYSIM [19] software was used. DAYSIM uses the 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 at 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 a 2^0 step. Thus, for each calculation point and each hour, the tilt angle is estimated using linear interpolation between adjacent tilt angle values.
The optical properties of the room surfaces are presented in the following table:

Property	Type	Value
Ceiling reflectance	Diffuse	0.8
Wall reflectance	Diffuse	0.5
Floor reflectance	Diffuse	0.3
Exterior lightshelf upper surface	Specular	void metal spec 0 0 5 0.95 0.95 0.95 0.873 0 void mirror reflector 1 spec 0 3 0.83 0.83 0.83
Exterior lightshelf lower surface	Diffuse	0.5
Glazing visible transmittance	Specular	0.6

Table 2. Typical room surfaces' optical properties

In order to investigate the behavior of the window-lightshelf system, it is desirable to have a theoretical model, capable of taking into account the reflected parts of both direct and diffuse illuminance. The assumptions used in the model are the following :

1. An isotropic sky model is used
2. The vertical window and lightshelf are of limited dimensions
3. Only the upper surface of the lighshelf is specular

The total hourly luminous flux (Φ) on the upper window is given by the following equation:

$$\Phi_{clerestory}=E_{dir\text{-}norm} * A_{dir} * \cos(\text{angle of incidence}_1) + E_{dir\text{-}reflected} * A_{reflected} * \cos(\text{angle of incidence}_2) + E_{diffuse\_hor} * (0.5-F_{upper\_window\text{-}lighshelf}) + E_{diffuse\_hor} * \rho_{lighshelf} * F_{upper\_window\text{-}lighshelf} * ((0.5*(1+\cos\beta_{lightshelf}))-0.5) + E_{total\_hor} * \rho_{ground} * (0.5-F_{upper\_window\text{-}lightshelf}) \qquad (2)$$

While the flux arriving in the lower part is calculated as :

$$\Phi_{view\_window}=E_{dir\text{-}norm} * A_{dir} * \cos(\text{angle of incidence}_1) + E_{diffuse\_hor} * (0.5-F_{window\_lightshelf}) + E_{total\_hor} * \rho_{ground} * 0.5 + E_{total\_hor} * \rho_{ground} * \rho_{lighshelf\_down} * (F_{window\text{-}ground}-0.5) * F_{window\_lighshelf} \qquad (3)$$

Where $E_{dir-norm}$ is the direct normal illuminance, A_{dir} & $A_{reflected}$ are the areas of the window illuminated by direct sunlight and reflected sunlight respectively, $E_{dir-reflected}$ is the reflected component of the direct normal illuminance, $E_{diffuse\_hor}$ and E_{total_hor} are diffuse and global horizontal illuminance, $\beta_{lightshelf}$ is the lightshelf tilt angle and ρ are the reflectances.

The F term represent the view factors associated with the surfaces of the model. Their calculation is tedious especially when the lightshelf has a tilt. For that reason, VIEW3D algorithm was used [24].

The above equations are solved using a geometry which is supported by two coordination systems, a local one (Local Coordinate System, LCS) and an overall (Overall Coordinate System, OCS). The OCS can be placed in any arbitrary point and its axes x,y,z point to the east , north and zenith directions accordingly. The relation between OCS and LCS is presented in the following graph.

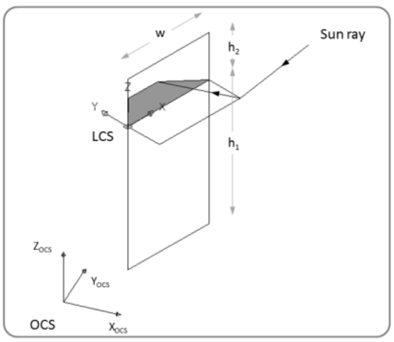

Figure 2. Geometrical framework for the analysis of window-lightshelf system.

Figure 2 also presents schematically the method used for the calculation of the clerestory window area exposed to a reflected beam. This method is based on the following steps:

1. Solar vector is estimated according to the OCS
2. The vector is transformed from OCS to LCS
3. If Local azimuth is <=180 then a sun ray is drawn to the right corner of the lightshelf as seen from the exterior (the left corner is used when azimuth >180)
4. Reflected ray direction and the intersection point with the plane of the clerestory window are estimated. Depending on its local coordinates, the area of the window exposed to the reflected beam is calculated analytically as follows

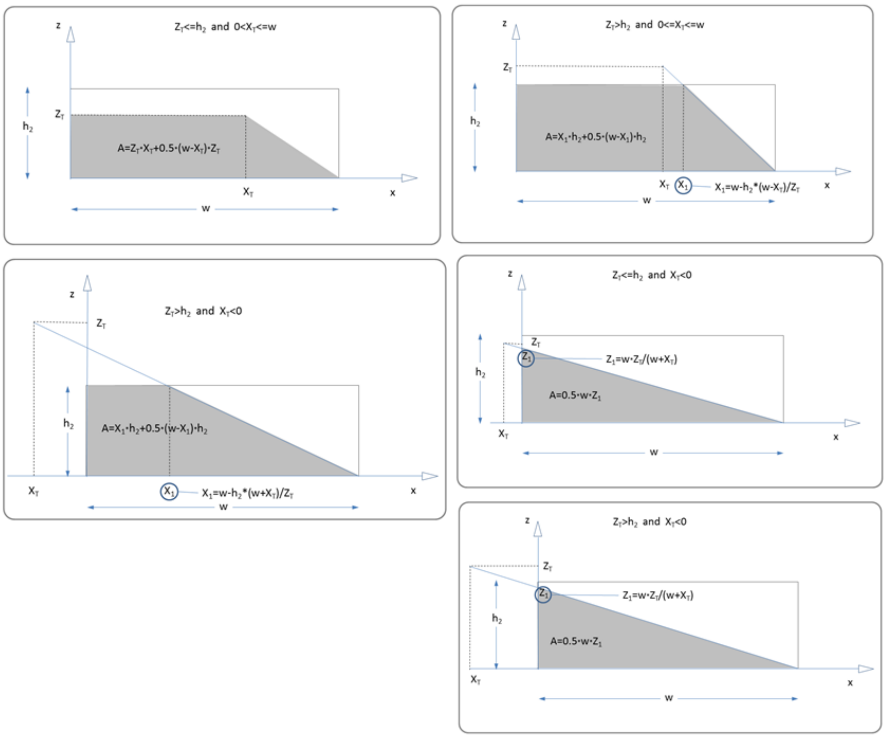

Figure 3. Estimation of the clerestory window area which is lighted by reflected sunlight.

A similar method is used for the shaded area calculation of the lower window. The above methodolody was used for the developing of a computer program capable of performing annual daylight flux calculations on an hourly basis for various window-lightshelf geometric configurations using Athens, Greece EPW weather files. Thus, not only the total luminous flux incident on the window can be compared on an hourly basis but also its upward and downward percentages. The figure below presents this analysis for Case#1 configuration during 3650 hours (8:00-17:00 per day).

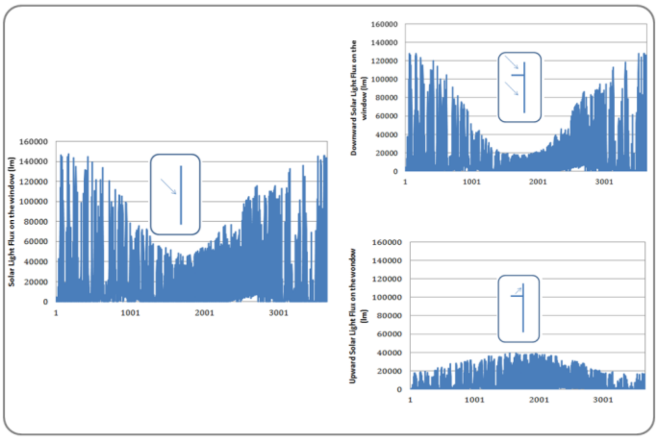

Figure 4. Comparing light flux on the window for case #1. Two alternative scenarios left (no lightshelf), right (sun tracking lightshelf).

As already mentioned, to examine the effect of the lightshelf tilt angle on daylight levels two typical office rooms with different depths and southern orientation were used. The main Radiance parameters used for the calculation were the following : (ambient bounces) ab 5, (ambient division) ad 2500, (ambient accuracy) aa0.1, (ambient resolution) a 300, (direct relays) dr 1.
The average illuminace and uniformity values for the two extreme cases (case #1 and case #5) are presented below.

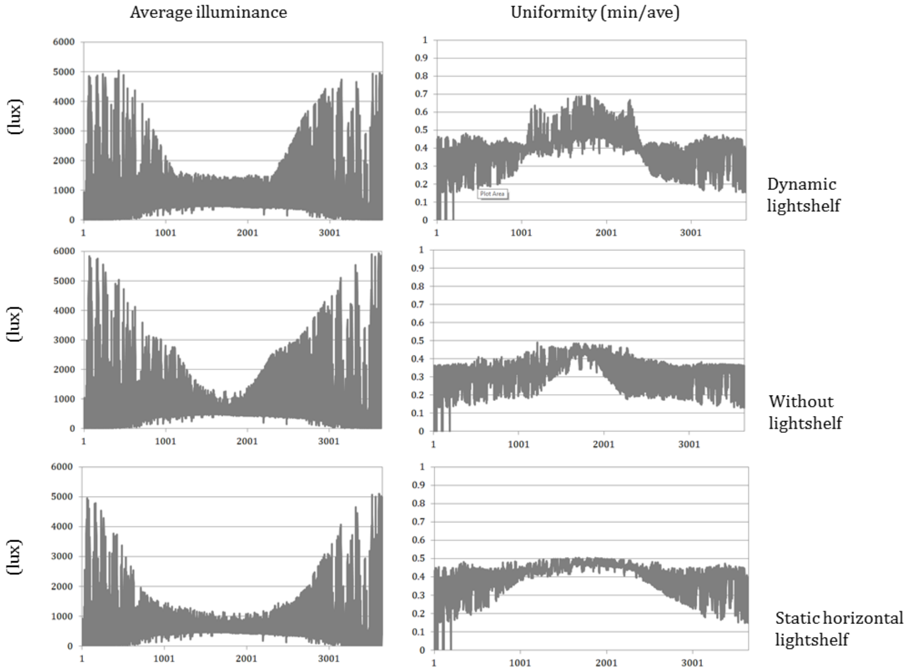

Figure 5. Hourly average illuminance and uniformity for three lighshelf configurations (Case #1)

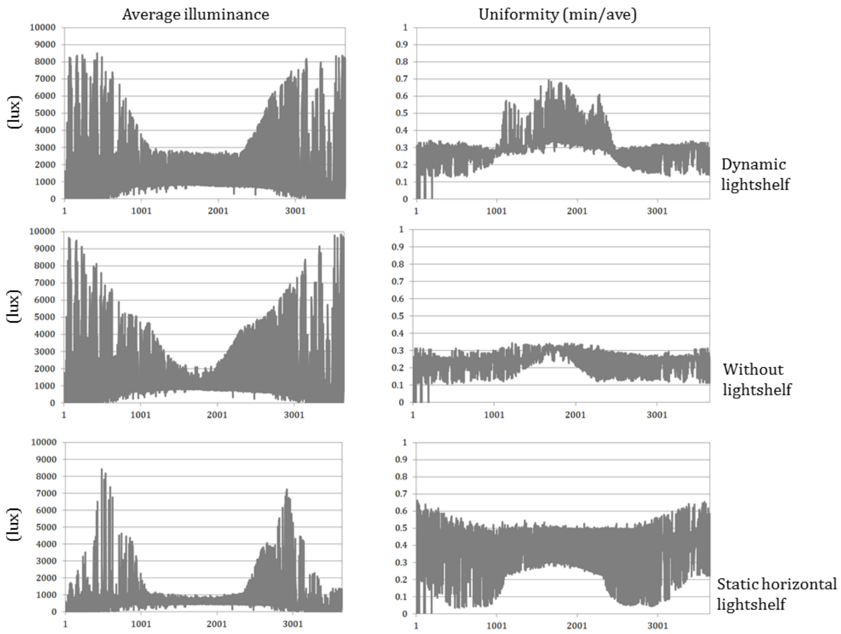

Figure 6. Hourly average illuminance and uniformity for three lighshelf configurations (Case #5)

Having hourly illuminance values , the Daylight autonomy (DA) values have been calculated across the measurement grids. DA at a point represents the percentage of occupied hours, on a yearly basis, during which illuminance values are greater than a predefined threshold, which in our case is 500 lux. The results are the following:

	Sun tracking Lighshlef	No exterior lighshelf	Static horizontal lightshelf
Case #1	78%	79%	79%
Case #2	90%	91%	89%
Case #3	92%	92%	91%
Case #4	78%	78%	76%
Case #5	89%	90%	89%

Table 3 . Daylight autonomy (DA_{500}) values for all cases.

Significance enhancement of lighting levels in the back of the room is affected mainly by the reflected sunlight especially for cases #4,#5. In these cases, 39% of the working surface area is outside the perimeter zone. The percentage of daylight zone in relation to gross floor area gives an indication of the possible lighting energy savings. Consequently, the challenge is to increase the size of these zones by bringing daylight to the building core since daylight harvesting dimming system is usually placed in these areas. In our case, DA500 values for the areas outside the perimeter zone are presented in the following table.

	Sun tracking Lighshlef	No exterior lighshelf	Static horizontal lightshelf
Case #4	29%	7.8%	7.5%
Case #5	57%	46%	52%

Table 4. Daylight autonomy (DA_{500}) values in areas outside the perimeter zone, for cases#4, #5 .

3. CONCLUSIONS

Simulations have been conducted to show the influence of a sun tracking lightshelf on possible lighting energy savings. Five case studies have been used representing two typical south-oriented office rooms with different depths and various Window to Floor ratios. The results indicate that :

- A suntracking lighshelf enhances working surface average daylight levels and uniformity , for all cases, during the summer period.
- During the winter months, it slightly reduces illuminance levels in comparison to cases where no lightshelf was used.
- Differences in DA_{500} are quite small (from 1.1 to 2.5%) between the alternative scenarios (suntracking lightshelf, no lightshelf, static lightshelf).
- DA_{500} values in the area outside the perimeter zone are considerably enhanced for cases #4 and #5. In case #4 (10%WFR), a 74% increase is observed, when comparing the solar tracking lightshelf and the static one. By doubling the size of the window (case #5), the increase is only 9%. These results justify the use of a lightshelf to increase the size of the daylight zone especially when the window size is small.

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