Performance assessment of an active sunlight redirection system in areas with different climate: A comparison

Antonis Kontadakis¹*, Lambros Doulos¹,², Aikaterini Mantzourani³, and Aris Tsangrassoulis¹

¹ Department of Architecture, University of Thessaly, Volos, Greece
² Lighting Lab, National Technical University of Athens, Zografou, Greece
³ School of Applied Arts, Hellenic Open University, Athens, Greece

kontadakis@uth.gr

Abstract. The aim of this work is to assess the impacts, both in terms of daylight efficiency and energy impacts, of an advanced daylighting system that utilizes a heliostatic configuration for sunlight redirection in a deep South oriented office room in two (2) different climate conditions. Conventional daylighting systems such as windows, and clerestories placed on building facades, for a variety of reasons, have been proven ineffective in solving the problem of deep interior daylighting. This effect even with the use of modern daylighting techniques can effectively maintain the required illuminances. In such cases, systems that are designed to take advantage both the direct and diffuse natural light while maintaining and improving occupant visual comfort, particularly at greater distances from the external walls can provide higher work-plane illuminance levels deeper into the space. The results summarized here demonstrate that, if selected according to daylight climate and integrated appropriately with electric lighting controls, the system can enhance daylight in building interiors and thereby promote energy savings. It should be noted, however, that the performance of these systems is dependent on daylight availability. Nonetheless, the information presented in this paper demonstrates the potential benefits and shortcomings from the use of sunlighting technologies in different climate zones.

1. Introduction

Conventional daylighting systems such as windows, and clerestories placed on building facades, for a variety of reasons, have been proven ineffective in solving the problem of deep interior daylighting [1, 2]. For spaces exceeding a certain depth in relation to window configuration, and orientation even with the use of modern daylighting techniques it is difficult to maintain the required illuminances as set by current standards and codes [3]. Daylight reaching the interior space is the sum of direct light, from the sun, reflected light by the atmosphere, sky, clouds, etc., and inter- reflected light, which has been scattered from the internal surfaces of the space. At distances further from the opening, the internally reflected component becomes the dominant source of illumination and thus the core of the space often requires additional support from artificial lighting. Extending the daylight area by increasing the window
size introduces a disproportional amount of solar radiation into the front part of the room to achieve a small increase in daylight levels at the back. This can result in an increase of the cooling loads which in turn can offset any electric lighting energy savings achieved by the adoption of harvesting techniques.

The challenge therefore is to develop means of utilizing both direct and diffuse natural light while maintaining and improving occupant visual comfort, particularly at greater distances from the external walls. In order to meet this need for deep indoor illumination, a variety of innovative daylighting systems, usually referred to as optical, sunlighting systems and/or light transport/guiding systems, have been developed [4, 5]. Innovative daylighting systems are designed to utilize primarily the direct component of daylight (sunlight) as the light source to actively track the sun or passively control the direction of sunlight and skylight to areas where it is required, without glare. Therefore, they are best suited for climates where sunny conditions occur more often, but there is a lack of knowledge regarding the energy performance of buildings equipped with such systems in various climatic zones.

The central focus of this paper is primarily to investigate the performance of an innovative sunlighting device, both in terms of daylight efficiency and its impacts on the energy balance of a test room in two (2) different climatic conditions. The results demonstrate that such a system can enhance daylight in buildings and thereby promote lighting energy savings while increase cooling energy consumption.

2. Methodology

An innovative daylighting system for side-lighted applications referred to as active sunlight redirection system (ASRS) was used based on the authors’ previous work [6]. It comprises a light shelf, mounted at about mid-window height, that captures sunlight using a heliostat configuration that actively tracks and collects sunlight, with the use of an array of five (5) mirrors as illustrated in Figure 1.

![Figure 1. Main configuration of the Active Sunlight Redirection System (ASRS).](image)

The ASRS can be attached to the building façade, on the window system and redirect solar beam radiation deeper into the room to specific locations on the ceiling plane. The system is designed to provide higher work-plane illuminance levels deeper into the room, away from the perimeter zone and thus offset the lighting energy requirements over a larger floor area.

For the evaluation a South oriented, deep office room was used as a reference case with dimensions: Width (W) 4 m, Length (L) 7 m. Height (H) 3 m, and a Window-to-Floor Ratio (WFR) of 10%, with surface reflectances for the interior floor, walls and, ceiling of 20%, 60%, and 80% respectively. The window sill was set at 1 m from the floor and had the following dimensions: Height 1.5 m and 1.6 m width, with a window frame of 0.05×0.05 m and visible transmittance (T<sub>vis</sub>) of 64%. In total, the South office room was simulated for three (3) conditions, with alternative fenestration system configurations as presented in Table 1, for two (2) cities in different climate zones according to [7] respectively, Athens, (Lat. 37.90°, Lon. 23.70°) and Thessaloniki (Lat. 40.52°, Lon. 22.97°), located in Greece. The performance assessment results were obtained by conducting simulations with Radiance [8] and EnergyPlus [9] engines respectively, while the data needed as input were created based on an algorithm capable of creating 3D-models of the proposed system together with the reflected sun-patch geometry on the ceiling [6].
Table 1. Description of the simulated cases.

| Scenarios     | Description                                                                 |
|---------------|-----------------------------------------------------------------------------|
| Base Case     | Reference office room with a conventional fenestration system, that is unshaded and unobstructed. |
| Lightshelf Case | Reference office room equipped with an external lightshelf Width (w) 0.5 m and Length (l) 1.6 m, equal to the length of the window. |
| Reflector Case | Reference office room equipped with the active sunlight redirection system (ASRS) with mirror dimensions 0.2×0.2 m. |

The light shelf was perfectly diffuse (80%) and the mirrors were assumed to have a specular reflectance of 98%. The mirror array was set to redirect the incoming sun rays towards the back end of the room, beyond the perimeter zone and the target of the reflected sun-rays was set at the ceiling plane 3 m from the floor and 6 m inside the space (measured from the interior wall).

For daylight simulations, an analysis grid of 0.5×0.5 m was used, resulting in 105 calculation points across the working surface at a height of 0.8 m above the floor level. The perimeter zone gap between the grid and the surrounding walls was set at 0.25 m. For the energy simulations, the reference office room was modeled to be part of an office building with only one facade exposed to the external environment. The office room was constructed to meet the minimum requirements of the national law N.3661/2017: Regulation on the Energy Performance of Buildings-KENAK [7] which describes the calculation methodology according to the European standards for the two (2) climate zones, from 08:00 to 18:00 (10 hrs) without counting Weekends.

Table 2. Radiance parameters for the simulated cases.

| Radiance Parameters        | Value |
|----------------------------|-------|
| Ambient Bounces (-ab)      | 5     |
| Ambient Division (-ad)     | 4096  |
| Ambient Sampling (-as)     | 2048  |
| Ambient Resolution (-ar)   | 1024  |
| Ambient Accuracy (-aa)     | 0.1   |
| Direct Relays (-dr)        | 1     |

Table 3. EnergyPlus parameters for the simulated cases.

| EnergyPlus Parameters      | Value            |
|----------------------------|------------------|
| Construction Set           | According to [7] -min. req. |
| Hours of Operation         | 10 hrs (08:00-18:00) |
| Mechanical Ventilation     | 0.047 m³/sec     |
| Infiltration               | 1 ACH            |
| Occupancy                  | 0.1 person/m²    |
| Electric Lights            | 14 W/m²          |
| Electric Equipment         | 15 W/m²          |
| Heating Set-point          | 20 °C            |
| Cooling Set-point          | 26 °C            |

An ideal dimming lighting system was modeled to reduce lighting energy consumption, having a linear relationship between the fractional input power and the fractional lighting output. The lighting energy savings for all cases were computed using Radiance and were converted into a schedule to be used by the EnergyPlus simulation engine. Lighting energy savings were calculated by using two (2)
calculation points inside the room: one (1) in the center of the perimeter (daylight) area as this was calculated by the EN 15193:1 [3] at 2.125 m, and the other at the center of the secondary (non-daylight) area, at the back end of the room (at 5.625 m). The design illuminance was set at 500 lx for both sensors. The simulation parameters for Radiance and EnergyPlus simulations are presented in Table 2 and 3 respectively.

3. Results and Discussion
The performance of the active sunlight redirection system (ASRS) was evaluated, and comparisons among the various fenestration configurations for the two (2) climates were carried out.

![Average Illuminance Distribution](image1)

**Figure 2.** Average annual illuminance distribution in the center-line for the simulated cases for Athens (Lat. 37.90°, Lon. 23.70°), and Thessaloniki (Lat. 40.52°, Lon. 22.97°), Greece.

Figure 2 illustrate the simulation results of the annual daylight performance of the examined cases for Athens (Lat. 37.90°, Lon. 23.70°), and Thessaloniki (Lat. 40.52°, Lon. 22.97°), respectively. Reflector Case corresponds to the fenestration system with the active sunlight redirection system, with a mirror area of 0.04 m². The Base Case and Lightshelf Case act as the reference cases and refer to reference office room (as described above) and the space with the lightshelf installed, respectively.

The results show that Reflector Case performs significantly better, compared to the reference cases, with an increase in the illuminance values through the operation of the movable mirrors, especially in the non-daylight zone of the space (>4.25 m, as calculated by the EN 15193-1 [3]) for both climate zones. Compared with the Base case, the office room equipped with the proposed system (ASRS) manages to increase illuminance levels in the secondary area (non-daylit zone) from 48% for Athens to over 64% for Thessaloniki. The area plot in Figure 3 illustrates the annual average illuminance distribution for all cases, on the working surface (0.8 m from the floor) where the difference in performance between the cases equipped with the proposed system and the reference cases is evident.
Figure 3. Annual average illuminance heat maps across the floor area of the simulated cases for the two (2) climate zones.

The uniformity ratios of the space for the simulated cases are presented in Figure 5. Uniformity values expressed as the ratio of daily min. illuminance to an average one, for all simulated cases. High illuminance values near the opening and lower at the back create a non-uniform lighting environment with high contrasts. The implementation of the proposed system (ASRS), manages to balance the illuminance distribution of the space where the external lightshelf presence diminishes the extreme variations between the front and back, providing a more balanced distribution. The lightshelf case manages to enhance uniformity by 17% compared with the base case for Athens and by 16% for Thessaloniki, whereas the reflector case by 56% and 54% compared with the base case for Athens and Thessaloniki respectively.

Figure 4. Uniformity ratios of the simulated cases for Athens (Lat. 37.90°, Lon. 23.70°), and Thessaloniki (Lat. 40.52°, Lon. 22.97°), respectively.

The simulation results of the energy performance of the space in terms of energy demand, and primary energy, under the various fenestration system configurations, are presented in Figure 5 and 6 respectively. According to the Greek national regulation [7], primary energy conversion factors are 2.9 for electricity while the efficiency of heating and cooling systems (using Energy Efficiency Ratio) for the reference building are 0.95 and 2.8 respectively. The effect of reflected sun-patches on the building energy balance has been calculated using EnergyPlus' "SurfaceProperty:SolarIncidentInside" object.
Using this method, the normal EnergyPlus calculation is replaced by a schedule of solar incidence values that were calculated with the help of the solar tracking algorithm.

**Figure 5.** Annual energy performance for the simulated cases in terms of energy demand for Athens (Lat. 37.90°, Lon. 23.70°), and Thessaloniki (Lat. 40.52°, Lon. 22.97°), respectively.

**Figure 6.** Annual energy performance for the simulated cases in terms of primary energy consumption for Athens (Lat. 37.90°, Lon. 23.70°), and Thessaloniki (Lat. 40.52°, Lon. 22.97°), respectively.
Comparing the Base case with the reflector case, the reduction in electricity use for artificial lighting is estimated at 23% for Athens and at 25% for Thessaloniki. The reduction increases when compared against the Lightshelf case by approximately 26% and 29% the two (2) climate zones, respectively. The internal heat gains may be useful when the space requires heating (during winter) but is counterproductive when the building requires cooling during summertime. In terms of cooling consumption there is an apparent increase, which is estimated at approx. 24% when compared with the Base case and 38% when compared with the Lightshelf case for Athens. The increase in cooling for Thessaloniki is estimated at 26% and 47% compared with the Base case and Lightshelf case, respectively. The reverse phenomenon occurs with the heating loads, where the addition of heat gains from the operation of the proposed system help reduce the heating requirements of the space. For Athens compared with the base case the reduction is approx. 15% and 2% for the Lightshelf case, whereas for Thessaloniki is 12% and 2.5%, respectively.

In general cooling systems must compensate for the heat generated by the lighting system, plus the addition of other internal loads such as equipment, people, etc. For the case equipped with the proposed system (ASRS), heat gains are added to the space from the mirror arrays and depend on their initial size and the intensity of solar radiation, more specifically the direct component. An interior view of the of the case with the proposed system is illustrated in Figure 7 for summer (6/21) at 12:00 for Athens, Greece.

![Figure 7](image_url)

**Figure 7.** Radiance synthetic fish-eye view of the ceiling, plane and cross section of the interior space equipped with the proposed system during summer solstice (21/06) at 12:00 for Athens (Lat. 37.90°, Lon. 23.70°), Greece.

The distribution of the additional heat gains by the operation of the of the five (5) mirrors versus the sun-patch area on the ceiling plane (of one (1) mirror) for Athens and Thessaloniki is presented in Figure 8, whereas Figure 9 shows a direct comparison of the heat gains entering the interior space for the two (2) climates by the operation of the proposed system. For the cases equipped with the active sunlight redirection system (ASRS), sun patches created on the ceiling depending on the size, shape and reflection characteristics of the mirrors. Specular reflection creates a sharply defined rhomboidal bright spot, and although the target point is fixed, the overall spot area changes over time due to the change in the relative sun-mirror position.

The size of each sun-patch on the ceiling ranges from approx. from 0.1 m² to 0.24 m² for both Climate zones. The overall area is dependent by the hour of the day where a higher sun position corresponds to a smaller sun-patch area. The increase in the target area from winter to summer is approximately 100%.
Figure 8. Annual distribution of internal heat gains in relation with the sun-patch area for Athens (Lat. 37.90°, Lon. 23.70°), and Thessaloniki (Lat. 40.52°, Lon. 22.97°), respectively.

Figure 9. Annual distribution of internal heat gains for Athens (Lat. 37.90°, Lon. 23.70°), and Thessaloniki (Lat. 40.52°, Lon. 22.97°), respectively.

4. Conclusions
Over the years there have been several developments in daylighting, and it seems that there is a tendency to move away from static towards more dynamic approaches. Advanced daylighting systems by effectively controlling how natural light is admitted and distributed inside a building space help improve the users’ productivity and well-being [10] while reducing the electric lighting power if coupled with a daylight responsive lighting control system [11]. The focus was primarily to investigate the impact of sunlight redirection for illuminating under-lit office areas through the utilization of this innovative daylighting concept system for side-lighting in different climates. Its performance was compared in a South façade of a deep office room with 10% Window-to-Floor Ratio (WFR), against two (2) alternative fenestration configurations both in terms of daylighting and energy performance for two (2) climate zones in Greece.

The results indicate that:
• The use of sunlight redirection indicates the potential to significantly improve the daylight levels of non-daylit areas, ranging from 48% for Athens to over 64% for Thessaloniki, and improvements in uniformity above 50%, when compared to an unshaded/unobstructed reference case.

• A reduction in electricity use for artificial lighting can be achieved for both climate zones, which is estimated at 23% for Athens and at 25% for Thessaloniki. The reduction increases when compared against the Lightshelf case by approximately 26% and 29%, respectively.

• Primary energy consumption for cooling is increased for both climate zones by approx. 25% when compared with the Base case. The resulting total primary energy consumption for the Base case is 94.7 and 123.3 kWh/m²yr for Athens and Thessaloniki respectively, whereas for the Lightshelf case is 96.7 and 128.2 kWh/m²yr, and for the Reflector case 95.2 and 121.1 kWh/m²yr, respectively.

The additional heat from direct solar radiation has a negative impact on the building’s energy balance. The electricity used for cooling increases significantly, which in turn diminishes the savings gained by turning off or supplementing the electric lights. The reverse phenomenon occurs with the heating loads, where the addition of heat gains from the operation of the proposed system help reduce the heating requirements of the space.

Controlling direct sunlight is always a tricky thing. Uncontrolled direct sunlight is substantially brighter than conventional artificial light sources and carries much more infrared energy thus contributing significant heat to any surface it hits, which in turn is accompanied by an increase in primary energy cooling consumption. It seems that a slight decrease in lighting consumption is always accompanied by an increase in cooling consumption. Uncontrolled direct sunlight and poorly insulated glazing, especially when South orientation, can have a profound impact on heat gains and loads, making the maintenance of occupant thermal comfort difficult.

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