Building and Environment xxx (2016) 1–13

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

An active sunlight redirection system for daylight enhancement beyond the perimeter zone

Antonis Kontadakis [a, *], Aris Tsangrassoulis [a], L. Doulos [b], F. Topalis [b]

[a] Department of Architecture, University of Thessaly, Pedion Areos, 38334 Volos, Greece
[b] Lighting Lab, National Technical University of Athens, Heroon Politechniou 9, 157 80 Zografou, Greece

A R T I C L E I N F O

Article history:
Received 19 June 2016
Received in revised form
23 September 2016
Accepted 24 September 2016
Available online xxx

Keywords:
Advanced daylighting systems
Heliostatic systems
Solar tracking
Daylight harvesting
Core daylight
Daylighting
Energy savings

A B S T R A C T

Over the past years, extensive research has been carried out in the creation of working environments that utilize natural light as their primary source of illumination. Transferring glare-free daylight into the core of the building can significantly increase lighting energy savings but it can increase cooling needs as well. Traditional daylighting systems mainly focus on controlling the incoming solar beam radiation, thus regulating the illuminance levels, usually near the perimeter zones. This paper proposes a sunlight redirection system that uses a number of movable mirrors, installed on a light shelf and capable of tracking the sun. Reflected sunlight is projected towards a specified, fixed target area on the ceiling. The theoretical framework for the operation of the proposed system is presented in detail, together with a daylight and energy analysis for the summer and winter solstices, representing the two extreme trajectories of the sun. Five cases were examined, representing various shading system configurations. The results indicate an increase of 99%, in the daylighting levels in the secondary (non-daylit) area during the summer solstice and a reduction of 21%, during the winter solstice, when compared to an unshaded, unobstructed reference case. If a case with a shading system (i.e. external static blinds) is used as a reference case, the proposed system increases the daily illuminance values during both solstices by 152% (summer) and 12.5% (winter). Unfortunately, there is a slight increase (<5%) in daily primary energy consumption. Simulations were performed using Radiance and EnergyPlus while the data needed as input, was created with a new algorithm capable of producing 3D models of the proposed system together with the reflected sunpatch geometry on the ceiling.

1. Introduction

Current environmental and energy concerns have been embedded into the design process of sustainable built environments. Building codes and standards have integrated ways of addressing daylight penetration into their guidelines. This is affected by user requirements and of course, energy savings concerns.

People have a natural attraction to daylight and tend to prefer daylit spaces to those that are artificially lit. Studies have shown that the use of natural light in buildings can have significant psychological and physiological effects on the health, well-being and performance of humans [1–4]. Studies have also shown that exposure to natural light can have a beneficial impact on the occupant's health by decreasing the occurrence of headaches, seasonal affective disorder (SAD), eyestrain, stress etc. [5–7].

Today, spaces are lit by a combination of daylight and artificial lighting. Thus, the adoption of daylight harvesting systems is an essential strategy in order to considerably reduce lighting energy consumption and peak electric loads. These systems offer the potential to reduce the electricity used, from 20% to 60% in optimal conditions [8–18]. An additional benefit is the reduction of the cooling energy [19,20] as the amount of heat generated by the lighting system is also reduced.

In the design process of a “good lighting environment”, both the quantitative and the qualitative parameters have to be met. The introduction of daylight in a space adds complexity to the problem due to its dynamic nature, since shading requirements have to counterbalance daylight adequacy. During the design process, there is always an effort to increase the usable

* Corresponding author.
E-mail address: kontadakis@uth.gr (A. Kontadakis).

http://dx.doi.org/10.1016/j.buildenv.2016.09.029
0360-1323/

daylighting area and this is achieved by placing regularly occupied spaces in the perimeter daylight zones.

Research has shown that vertical openings can, in most cases, sufficiently and effectively illuminate an area as far as 5 m away from the window-wall [21,22] leaving areas that are further away from the opening under-lit and as a result these still require additional support from artificial lighting. Attempts to extend the daylight area and thus the lighting control area by increasing the apertures, introduce a disproportional amount of solar radiation into the front part of the room and usually small gains in daylight levels are achieved at the back. Therefore, an increase in cooling loads can offset the electric lighting energy savings. In addition, the non-uniform illuminance distribution within the space together with a probability for glare, can result in an uncomfortable lighting environment for the users.

Traditional daylighting techniques [13,23–27] have certain shortcomings when it comes to illuminating deep spaces, thus over the years a variety of innovative daylighting systems has been proposed. These systems rely on the proper handling of diffuse/direct illuminance and redirecting daylight to areas away from the openings, usually onto the ceiling in locations above eye level.

Various reviews regarding daylighting devices and attempts to classify them based on their operation and the type of light they were designed to utilize, have been presented [25,28–34].

Over the years, several designs have been proposed, from reflecting blinds, light shelves and light transfer tubes [34,35] to anidolic [9,36,37] and optical lighting systems [30,38,39], as well as static or solar tracking heliostatic configurations [40] for daylight redirection. Tsangrassoulis et al. [41] reviewed automatically controlled light shelves and suggested a dynamic light shelf capable of redirecting sunlight into the core of the building, by controlling its tilt angle according to the position of the sun and a predefined target area on the ceiling. The results showed an increase in the size of the daylight area especially when the size of the window was relatively small, by improving the average daylight levels and uniformity during the summer. Khosravi et al. [42] proposed a core sunlight system consisting of active and passive components. A sun tracking collector and a light guide system were suggested to harvest sunlight and redirect it into the interior. The assessment of the performance of the system showed potential in providing useful illumination. Scartezzini and Courret [43] investigated the daylight performance of three (3) alternative anidolic system configurations (anidolic ceiling, integrated anidolic system, anidolic solar blinds) and the results yield substantial improvements in the daylight levels on the work plane. All the systems showed increased daylight levels at the back end of the given space and improvements in the uniformity without estimating the impact on building energy balance.

Thus, the challenge is how to admit sufficient daylight as deeply as possible into a space, reducing not only lighting energy consumption but the overall energy consumption as well. The aim of this paper is primarily to investigate performance both in terms of daylighting and energy consumption of an advanced daylighting system referenced as “active sunlight redirection systems (ASRS)” that utilizes direct beam radiation for daylight illumination.

2. Active sunlight redirection system

The active sunlight redirection systems (ASRS) can be attached to the building façade, on the window system and redirect solar beam radiation deeper into the space to specific locations on the ceiling plane. It comprises a horizontal surface, mounted at about mid-window height, that captures sunlight using a heliostat configuration that actively tracks and collects sunlight, by utilizing three (3) mirrors in an array, as presented in Fig. 1. The operation principle of the mirror array is rather simple. As the sun moves across the sky, the mirrors adjust their positions in order to track the sun and keep the reflected light fixed on the ceiling plane.

The dimensions of the mirrors are the same, 0.2 m width and 0.2 m length, resulting in an area of 0.04 m^2 each. It should be noted that the number, shape and size of the mirrors depends on the limitations of the dimensions of the window (width and length). The system can accommodate a specific number of mirrors, which can rotate freely without interference from their neighboring mirrors.

The aim of this paper is primarily to investigate performance both in terms of daylighting and energy consumption of an advanced daylighting system that utilizes direct beam radiation for daylight illumination.

The design of the proposed system was based on the following parameters:

1. The reflected sunlight has to be transferred through the clerestory window, the maximum height of which (~0.5 m) affects the maximum dimension of the mirrors so that the reflected luminous flux is directed within the room without loss (due to the façade and the window frame blockage). The same results can be achieved using smaller dimension mirrors, but they have to increase in number, thereby increasing the complexity of the system.
2. The distance between the mirrors is such that they can freely rotate avoiding contact with any neighbor surfaces (mirrors, shelf and façade-wall) and ensure that in extreme positions of the sun, mutual shading is avoided, during operation.
3. The system has to be mounted on a stand, which in our case is the external shelf offering shading to the lower view-window and partially satisfies the criteria of architectural integration.
4. Its ability to increase illuminance levels in areas beyond the perimeter zone, especially during the summer, when the sun's trajectory is quite high. In our case, the criterion was the doubling of illuminance levels in this zone, in comparison with the reference case (no shading at all).

Solar tracking can be implemented either by utilizing a Single-Axis system that tracks the sun from East to West using a single pivot point (rotating around a fixed horizontal axis), or by using -for greater accuracy-a Dual-Axis sun tracking system with two pivot points (two axes of rotation) as illustrated in Fig. 2.

For Dual-Axis sun tracking systems, the most commonly used method is the Azimuth-Elevation (AE) [44]. In the AE tracking method, one of the tracking axes of the reflector points towards the Zenith (Azimuth-axis), while the other (Elevation-axis) is perpendicular to the first and tangent to the frame of the reflector. Over the years, new methods to harness solar rays have emerged [45–47]. Among them, the Spinning-Elevation (SE) method [45,47] is considered to be more advantageous compared to the AE method, by minimizing the aberration effect. It has better optical efficiency and consumes less power (from 4.8% to 9.3%). In addition, the number of control components can be significantly reduced, which in turn, results in less fabrication costs [48–51]. In the SE tracking method, one of the tracking axes of the reflector, points towards the target (Spin-axis) and it is responsible for maintaining the reflector normal within the tangential plane, while the other (Elevation-axis) is perpendicular to the Spin-axis and tangent to the frame of the reflector and adjusts the reflector normal within the tangential plane, until it bisects the sun position vector and the target position vector.

Given that the sun and the target are independent of the sun tracking method used, both methods achieve the same incident

Please cite this article in press as: A. Kontadakis, et al., An active sunlight redirection system for daylight enhancement beyond the perimeter zone, Building and Environment (2016), http://dx.doi.org/10.1016/j.buildenv.2016.09.029