The effect of the daylight zone on lighting energy savings

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Abstract. Daylighting is the cornerstone of low energy building design. Therefore, the adoption of a daylight – harvesting lighting control system can substantially increase lighting energy savings. These are strongly depended on the determination of daylight zones (DZ) which in turn help to identify the lighting loads that must be controlled separately. The Daylight Zone (DZ) is defined in ANSI/ASHRAE/IES Standard 90.1-2016 as the floor area substantially illuminated by daylight. However, the DZ is defined differently in several standards and building codes. Lighting design plays also an important role since it determines the number of luminaires in the daylight zone and thus the resulted energy savings due to the daylight harvesting techniques. Each one of these luminaires inside the DZ should be dimmable and must be controlled by either a stand-alone photosensor or one photosensor per control zone. In order to investigate the influence of the DZ in lighting energy savings several simulations were conducted in five (5) office spaces - part of the reference office building used to determine cost optimal energy performance for office buildings in Greece. DZ area was estimated using three (3) different definitions according to a) EN 15193.1 as implemented in Greek regulation of Energy Efficiency in Buildings, b) CEN Technical Committee 169/WG11 ‘Daylight’, and finally c) using dynamic daylight metrics for typical working hours in all four cardinal orientations. Results indicate that due to the differentiation of the DZ depth as this is calculated by the aforementioned methods, there is an associated variation of the calculated lighting energy savings. The extend of the DZ varies between 30-100% of the total area in each office when DZ is calculated using the geometrical method, 50-100% when daylight factors are used and 30-60% with dynamic daylight metrics. The number of luminaires within the DZ vary between 30-100% in the same space depending on the calculation method, the geometry of the room and the Window to Floor Area. As already mentioned, lighting energy savings for the examined test spaces vary, since these are strongly depended on method for the calculation of the DZ’s depth from 61% to 89%, 53-72% and 69-91% correspondingly.

Keywords: Daylight harvesting, Daylight zone, Daylight metrics, Lighting energy savings, Photosensors, Office building.

1. Introduction

Prior to the 1940s daylight was the primary source of illumination in residential and commercial buildings. Myriad advancements in artificial lighting design precipitated a relatively quick transition toward present design standards where artificial lighting systems provide all or most of the necessary lighting levels and are designed to supplement natural light. Today’s architects and lighting designers attempt to use daylight as the dominant light source as much as possible. This application of daylight
is based on energy concerns and user requirements, as it is known that during the conceptual building design, daylight utilization can have a significant impact both on energy performance as well as the creation of comfortable indoor environments. These concerns were the catalyst for the resurgence in daylighting popularity, leading to a variety of innovations in design practices and control strategies, effectively incorporating daylight into lighting designs while mitigating the potential problems associated with direct sunlight [1].

Studies have shown that daylight can achieve significant energy savings using integrated lighting control strategies (artificial and daylight) by harvesting the daylight levels inside the interior space and adjust the electric lighting system output to maintain the desired lighting task levels. The potential offered by these systems reduce the lighting energy use from 20%, up to 60% in optimal conditions [2, 3]. An additional benefit is the cooling energy reduction as the amount of heat generated by the lighting system is also reduced [4, 5]. Furthermore, there is an extensive research that suggests the use of natural light in buildings can promote human health and performance [6]. Studies have also shown that proper use of daylighting can have beneficial impacts on occupants’ health by decreasing the occurrence of headaches, Seasonal Affective Disorder (SAD) and eyestrain [7].

In the design processes of well-lit environments, there are three factors that should always be considered: The quantity, the quality and the distribution of light. The introduction of daylight in a space adds a complexity to the problem. The dynamic nature of daylight includes a temporal quality and quantity over time and poses new challenges in effectively illuminating an interior space, making it a less reliable light source. Also, there is a limit in illuminating a building exclusively by daylight. Daylight penetration can be severely suppressed within a deep room i.e. dullness in the far end of the room and high brightness near the window. Despite there are several types of daylight systems [8-12], daylight distribution is not uniform and decreases rapidly with the distance from the window. This effect becomes more apparent in deep spaces where even with a fully glazed façade, daylight is not able to effectively illuminate the space without additional support from artificial lighting. It is obvious that in some interior spaces, daylight cannot substitute for all electric lighting, even on bright days.

Today spaces are lit by a combination of daylight and artificial lighting [13, 14]. These areas are configured to take advantage of the use of natural light and either supplement electrical lighting systems or when possible replace artificial lighting altogether using photosensors [15]. One of the biggest issues in the design process is to find an optimal balance between daylight and electric light, with respect to occupants’ visual needs and energy restrictions [16]. Therefore, when designing buildings or spaces by incorporating daylight, designers must first determine the penetration of natural light into a room by identifying the areas (lighting control zones) inside the space where lighting loads can be separately controlled [17, 18]. Side lighted spaces are spaces where daylight enters the interior space through vertical fenestration systems such as windows or other openings. All spaces with fenestration systems are affected by daylight, and in such spaces, the daylighting design should be considered as the first step in the lighting design process by identifying the lighting control zones inside the room.

Numerous studies by institutions such as the IESNA (Illuminating Engineering Society of North America) and CIBSE (Chartered Institute of Building Service Engineers) have resulted in illuminance recommendations. For instance, the EN 12464-1:2011 Light and lighting- Lighting of workplaces. Part 1: Indoor workplaces [19], provides the lighting requirements for different work situations. In office spaces for tasks like writing, typing, reading, data processing etc. the recommended design levels of illumination are 500 lx on the work-plane. According to CIBSE Lighting Guide LG10: Daylighting and Window Design [20], the working plane is defined as the horizontal, vertical or inclined plane in which a visual task lies. The working plane is normally taken as 0.7 m or 0.8 m above the floor (depending on the adopted standard each time) for office spaces. The Illuminating Engineering Society of North America (IESNA) [21] has also established a set of minimum recommended illuminance levels for a variety of visual tasks and space functions. In these requirements for good lighting, no discrimination is made between daylight and artificial light consequently, the lighting system is designed to deliver the required illuminance levels evenly across the work-plane regardless other
sources of illumination (the sun) if present also contributing. Current practice suggests that the lighting systems can be separated into a general one providing 100lx or 300lx and a local one capable to achieve 500 lx on the task area. The daylit area in a building corresponds to the area in which target illuminances or other illuminance-based criteria are routinely met by daylight alone. Daylighting can be utilized to accommodate various design objectives like the impression of a well-lit environment; achieve illuminance targets for illumination of the space; reduce energy consumption in artificial lighting; promote occupants’ well-being and productivity. Dependent on criteria formed to facilitate various design objectives, like daylight, the daylit area can be re-formed and reshaped.

There is an ongoing effort in Greece to minimize energy consumption in the building sector [22 - 31]. Since daylight is abundant during the year, there is a lost opportunity for energy savings using daylight controls such as photosensors in office buildings. Therefore, the transition between the daylit and non-daylit zones can be achieved in various ways based on objectives set in the design process. Deferent priorities require different methods of approach. The scope of this paper is to examine these opportunities, by optimizing the selection of the daylight zones using three (3) different methods of calculation according to a) EN 15193 [32] as implemented in Greek regulation of Energy Efficiency in Buildings [33], b) CEN Technical Committee 169/WG11 ‘Daylight’ [34] and c) using dynamic daylight metrics (Daylight Autonomy, DA) for typical working hours in all cardinal orientations. Finally, their corresponding impact on lighting energy savings in the selected office room configurations was calculated.

2. Methodology
To assess the lighting energy saving potential from the corresponding daylight zones, a series of simulations were carried out, for five (5) typical rooms based on the reference office building for the calculation of the cost-optimal levels of minimum energy performance requirements for Greece, [35], as illustrated in Figure 1. The performance of each configuration was assessed based on computing the extent of the daylight area for three (3) alternative methods as presented in Table 1.

The performance assessment results for the DA and DF were obtained by conducting simulations using the parametric design program Rhino/Diva for Rhino plug-in [36] and Relux software [37] respectively for Athens, Greece (Lat. 37.90°, Lon. 23.70°) using climate data obtained from the EnergyPlus Weather Data website [38]. The test rooms were constructed to meet the minimum requirements according to Greek Energy efficiency regulation of buildings [33] which describes the methodology for calculating buildings’ energy consumption.

![Figure 1: Office room configurations, with their dimensions in meters respectively from the reference office building.](image)

The analysis grid created for each space configuration was set 0.5×0.5 at a height of 0.8 m from the floor. For the definition of the window geometry, a clear double-glazing system was used, with a glazing visible transmittance of 80% and a frame ratio of 20%. The rooms’ interior wall; ceiling and; floor reflectances were 70%, 70%, and 20% respectively. Figure 2 summarizes the methodology.
Table 1. Daylight zone (DZ) calculation according to the methods implemented in this study.

| Method | Description |
|--------|-------------|
| **Method A**: According to EN 15193.1, as implemented in Greek regulation of Energy Efficiency in Buildings. | The daylight area is calculated based on the window heads’ height (the distance from floor to window lintel) using the equation \( DZ = 2.5 \times (WHH - H_{task-area}) \). Where, DZ: Daylight zone depth, WHH: Window head height, \( H_{task-area} \): Height of task area (reference plane) above the floor. |
| **Method B**: According to CEN Technical Committee 169/WG11 'Daylight'. (Two scenarios using DF=2.6% as primary and DF=1.5% as extended) | The daylight zone is calculated based on the Daylight factor (DF) metric which is the ratio between the mean illuminance in a space and that from an unobstructed external sky, generally assumed to be the CIE overcast sky. |
| **Method C**: According to Climate Based Daylight Metrics (CBDM). (Four scenarios using North, East, South and West orientation) | The daylight area is calculated with the use of the Daylight Autonomy (DA) metric and requiring a minimum target value, equal or above 500 lux at each sensor point across the analysis area for 50% of the working hours, in all cardinal directions. |

Figure 2. Flowchart of the proposed methodology of the research.

Initially, the artificial lighting system was designed for all test cases, making possible the estimation of the number and location of the luminaires. The design illuminance for office rooms was set at 500 lx, with a uniformity ratio \((U_o)\) of 0.6 (minimum to average illuminance) for the whole reference plane as they are defined by the European Norm 12464-1, 2011 [19] and the Greek Energy efficiency regulation of buildings [33].

Minimizing the number of luminaires, is crucial for the economic viability of an office renovation [14]. The furniture arrangement of the test cases is unknown, so the whole office area was defined as reference plane. Table 2 presents the technical specifications of the luminaires used while figure 3 shows the results from the photometric analysis as they were obtained from RELUX simulation tool [37]. The average installed power was equal to 6.8W/m².
Table 2: Technical specifications of the used luminaire.

| Parameter          | Value          | Photometric polar diagram |
|--------------------|----------------|---------------------------|
| Luminous Efficiency| 112 lm/W       |                           |
| Luminous Flux      | 2800 lm        |                           |
| Power              | 25 W           |                           |
| LxBxH              | 0.6x0.6x0.05 m |                           |

3. Results and Discussion

3.1. Number of luminaires inside a daylight zone

As mentioned in the previous paragraph, three methods where used for the estimation of the DZ. The results for all examined scenarios are presented in Figure 4.

Using Method B (with DF=1.5%) for the estimation of DZ’s depth (Figure 4), results in the largest DZ which essentially is the whole area of the test room. Using Method C, only the luminaires closest
to the windows are included in the calculated DZ. All room configurations show similarities regarding the extent of the DZ and thus the area of lighting control with the only exception being office room 5 where with method B the whole area of the room can be considered as DZ. This is due to the room dimensions, where the extended width along with the shorter depth allows deeper daylight penetration.

Table 3: Number of luminaires installed in a Daylight Zone

| Office room | Luminaires installed in Daylight Zone | Total number of luminaires |
|-------------|--------------------------------------|---------------------------|
|             | A | B | C | Orientation | West (C1) | North (C2) | East (C3) | South (C4) |  |
| 1           | 2 | 2 | 2 | 2          | 2         | 2          | 2         | 4          | 4  |
| 2           | 2 | 2 | 2 | 2          | 2         | 2          | 2         | 2          | 4  |
| 3           | 3 | 3 | 5 | 3          | 3         | 2          | 2         | 6          | 6  |
| 4           | 2 | 2 | 4 | 2          | 2         | 2          | 2         | 6          | 6  |
| 5           | 6 | 6 | 9 | 6          | 5         | 6          | 6         | 9          |    |

3.2. Energy savings

Lighting energy savings were calculated according to the Greek Energy Efficiency Regulation of Buildings in which a predefined percentage (30% for office buildings) is assigned in each luminaire located in the DZ, representing annual lighting energy savings. For the three methods used to calculate the DZs this percentage differs as presented in Table 4. Using these percentages for each luminaire, the annual lighting energy savings for the whole room was calculated (Table 5). The operational schedule of the test rooms is between 8:00-18:00 for the whole week except weekends.

Table 4: Defined energy savings per method per daylight zone

| Method | Energy savings for luminaire using photosensor inside Daylight Zone | Source |
|--------|---------------------------------------------------------------|--------|
| A      | 30%                                                          | EN 15193-1, Greek Energy efficiency regulation of buildings [32,33] |
| B      | 50%                                                          | Standard CEN/TC 169/WG 11, Daylight in Building [34] |
| C      | 50%                                                          | Daylight Autonomy, DA500lx |

Table 5: Calculated energy savings per room depending the number of luminaires located in daylight zone for methods A to C.

| Office room | Method used for the determination of the Daylight Zone |  |
|-------------|-------------------------------------------------------|---|
|             | A | B | C | Orientation | West (C1) | North (C2) | East (C3) | South (C4) |  |
| 1           | 15% | 25% | 25% | 25% | 25% | 25% | 25% | 50% |
| 2           | 15% | 25% | 50% | 25% | 25% | 25% | 25% | 25% |
| 3           | 15% | 25% | 42% | 25% | 25% | 25% | 17% | 17% |
| 4           | 10% | 17% | 33% | 17% | 17% | 17% | 17% | 17% |
| 5           | 20% | 33% | 50% | 33% | 28% | 33% | 33% | 28% |
| Average     | 15% | 25% | 40% | 25% | 24% | 23% | 28% |

It is evident that the method used to estimate lighting energy savings due to daylight harvesting by the Greek Energy Efficiency Regulation of Buildings is not accurate, underestimating the potential savings. In order to prove that, an extra scenario D was examined for each test case. Lighting energy savings were calculated through the estimation of hourly daylight illuminance values in areas beneath the luminaires as the work plane illuminance reference at the standard desk height for overcast and clear sky conditions. The day selected was the 21/3 and the target illuminance was 500 lx. An ideal continuous dimming system was used with the fractional lighting output ($f_L$) is calculated according to the relationship:

$$f_L = \max[0, (500 - \text{Daylight levels at a point})/500] \quad (\text{Eq. 1})$$

When the minimum lighting output is achieved ($f_{L,\text{min}}$), there is a minimum power input $f_{P,\text{min}}$. 
Both values depend on the type of the driver. The relation between power \( P \) and \( L \) is:

If \( f_L < f_{L\text{min}} \) \( \rightarrow f_P = f_{P\text{min}} \) \hfill (Eq. 2)

If \( f_{L\text{min}} \leq f_L \leq f_L \) \( \rightarrow f_P = \left( f_L + (1 - f_L) \times f_{P\text{min}} - f_{L\text{min}} \right) / (1 - f_{L\text{min}}) \) \hfill (Eq. 3)

For the present calculation \( f_{P\text{min}} = f_{L\text{min}} = 0 \).

Each luminaire was controlled separately thus the total energy savings was averaged from the different dimming profiles of each luminaire. The calculated energy savings are presented in Table 6. For the overcast sky conditions the average energy savings for the examined office building using method D was 46% while this percentage varied from 56% to 75% for all four cardinal orientations and clear sky condition. Comparing Tables 5 and 6 it is evident that the predefined energy savings suggested by the national standards underestimate the actual energy savings from daylight harvesting. In Method A, using predefined energy savings 30% per luminaire installed in the DZ the average energy savings are equal to 15%, while in Method D, using only overcast conditions the average energy savings are 46%. This difference of 67% is getting larger for clear sky conditions and different orientations.

![Figure 5: Daylight levels per zone controlled by the 4 photosensors installed in each luminaire in Office room 1 facing South, (21/3 equatorial, clear sky).](image)

| Office room | D (clear sky) | D (Overcast) |
|-------------|---------------|--------------|
|             | Orientation   |              |
|             | West (D1)     | North (D2)   | East (D3) | South (D4) |
| 1           | 84%           | 69%          | 80%       | 87%       | 56% |
| 2           | 78%           | 59%          | 71%       | 77%       | 50% |
| 3           | 69%           | 46%          | 60%       | 69%       | 38% |
| 4           | 58%           | 44%          | 56%       | 54%       | 37% |
| 5           | 51%           | 64%          | 77%       | 87%       | 50% |
| Average     | 68%           | 56%          | 69%       | 75%       | 46% |

4. Conclusions

Current environmental and energy concerns have been embedded in the design process of sustainable built environments creating different set of priorities that needs to be addressed. One of the main reasons towards the use daylight is code compliance. Daylight harvesting methods are key elements in these codes. Daylight contributes to the illumination of the space by creating a constantly changing weather dependent indoor environment due to its dynamic nature and the design of an optimum luminous environment can be achieved only if an integrated approach (daylight and artificial) is adopted. A holistic method of estimating the actual daylight depth by considering all the variables is needed. Unfortunately, the method that is used in the Greek Energy Efficiency Regulation of Buildings, incorporates fixed lighting energy savings percentages for the luminaires installed in the DZ. The focus of this paper was primarily to investigate the impact of the daylight zone in lighting
energy savings using three alternative methods (A, B and C) to calculate the DZ and a method D depended on the actual amounts of daylight detected in each luminaire for a reference day (21/3).

The results indicate that:
- The percentage of savings is influenced by the size of the offices and mainly by the geometric characteristics of the space and the fenestration system.
- Higher lighting energy savings are observed in shallow office rooms like office room 5 with the openings located at their long side, regardless of their dimensions. In these offices’ daylight can be utilized more effectively resulting in daylight zones that cover most of the working area. On the contrary, in offices with an elongated floor plan having openings along the short side, lighting energy savings are reduced.
- By comparing the corresponding daylight zones calculated by the three methods (A to C), it is ascertained that the larger the area that covered by the DZ, the lighting energy saving potential is increased. At this point, another issue must be mentioned. Lighting energy savings are related to the number of luminaires in the DZ; thus, lighting design plays a crucial role by selecting luminaires of the proper wattage and size.
- As already mentioned, the Greek Energy Efficiency Regulation of Buildings assigns a fixed lighting energy percentage in each luminaire in the DZ. Using this percentage and calculating the size of the DZ with Methods A to C the average lighting energy savings were varied from 15% (Method A) to 40% (Method B2). Repeating the same calculation using simulation data for estimating daylight illuminance (Method D) the average energy saving was 46% for overcast conditions and from 56% (North) to 75% (South) for clear sky conditions.

We conclude that the total area of the reference office building can be subdivided into several smaller lighting control zones. This will permit better regulation of the artificial lighting system and therefore increased lighting energy savings can be achieved. Moving towards the age of the nZEB, the dynamic methods for calculating energy savings become a necessity. The fixed lighting energy savings percentages for each luminaire in the DZ, is a quite simplistic approach but it doesn’t promote efficiency. Moreover, the current lighting design doesn’t follow the task lighting design [14, 19] resulting in increased installed lighting power. Combining task lighting design with the placement of the working planes inside the DZ could result not only increased energy savings but also a more pleasant working environment.

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