Comprehensive analysis of active and passive daylighting towards power savings in an office room

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Abstract. A comprehensive method is presented to simulate illuminance distribution for two office room designs with same area of 7.8 m² each: room 1 has a window whilst room 2 has no window. The integration of passive daylighting system and light emitting diodes (LEDs) is adopted for illuminating room 1, while the integration of active daylighting system and LED lighting is adopted for illuminating room 2. The effectiveness and power savings are analysed for the aforementioned two cases. The impact of using LED lighting to control the illuminance and light distribution (uniformity) of light is also studied. For both cases, simulation was performed for a selected day under three sky conditions: clear sky, mixed sky and overcast sky using a software called DIALux 4.13 to obtain the average illuminance in the rooms and the power saved via the use of active and passive daylighting systems. Results obtained showed that active and passive daylighting systems are both effective for power savings depending on the location of rooms and time of the day. Also, active daylighting system is more effective under clear sky, while passive daylighting system can be effective under clear or mixed sky.

1. Introduction

Energy consumption of lighting in buildings is estimated as 20% worldwide varying from country to country [1]. The lighting energy consumed by buildings is generally produced by the combustion of fossil fuels which raises serious environmental concerns mainly climate change and air pollution. Since mid-1800’s, the concentrations of CO₂ in the atmosphere have increased by about 40 % [2]. Many solutions of reducing CO₂ emission have been proposed; but most prominent is the use of renewable energy such as solar energy instead of fossil fuel for power generation. The power generated is also employed to provide electricity for illuminating buildings. However, instead of changing the solar power to electrical power and then from electrical power to photonic power for illumination; it is more efficient, pollution free and cost saving to directly send the visible part of natural light into the building for daylighting during the daytime. Daylighting systems reduce lighting energy consumption by using natural light to provide the required illumination in a room during the day depending on the cloud condition. This has been demonstrated in previous studies. Ihm et al. (2009) carried out a study to investigate the effect of daylighting performance for various combinations of building size, including its window size, glazing type, dimming daylighting controls and their settings for some USA and international locations. Their results showed that significant energy savings of up to 60 % can be incurred annually using dimming control strategy specifically for a building space of 2.9 m (W) by 5.5 m (L) with floor to ceiling height of 2.5 m and two double pane windows in the west façade of the room exposed fully to natural light [3]. Osama abed el-Raoufa et. al (2018) presented and investigated a case
study of a 156 m² building area in the new rural area of Farafra oasis in Egypt with the use of daylight for energy saving. DIALux software was used to simulate daylighting in various areas of the building for all four seasons of the year while the hours of daylight were calculated for the times when artificial lighting was not required. From this, a total energy savings of 83.1 kWh was calculated [4]. Shishegar and Boubekri (2017) also carried out a simulation study on the effect of the use of daylight control systems in office buildings located in hot regions to save 30 % of overall electrical energy consumption: 85 % in lighting energy 15 % in cooling energy [5]. With the use of daylighting, electric lighting consumption in commercial buildings can be reduced by 50–70 % [6]. Passive daylighting systems such as windows are the easiest and most common daylighting methods that are installed in most buildings for natural ventilation and visual comfort. The daylighting levels in a room drops proportionately with respect to the window location in the room, size of the room and cloud condition. For very small rooms, windows alone might provide sufficient illumination during the day but it is vice versa for a bigger room. Thus, LED’s or active daylighting systems are required for compensation of the daylight from windows and for use at night when there is no daylight. LED is an environment-friendly, energy efficient lighting source that consumes less energy and has a long life cycle [7]. Rooms without windows due to their location in the building, can be illuminated via electric lighting and or via daylighting from either active or passive daylighting systems to conserve energy. In this paper, two office rooms are analyzed - one with a window and the other without a window. The room with a window has LEDs to compensate the daylight from the window; while the room without a window has an active daylighting system compensated with LEDs to provide daylighting for energy savings. The importance of this study is to show how a combination of these daylighting systems can lead to electrical energy savings. The use of active and passive daylighting systems can lead to power savings by offsetting electric lighting energy [8]. In this paper, theoretical analysis has been carried out using DIALux 4.13 software and formulas obtained in a previous paper on two-stage non-imaging solar concentrator (2S-NISC) and fiber-optic by Chong et al, 2017 [9] to simulate the illuminance distribution and calculate the power savings in both room designs.

2. Case study and methodology

For this case study, two office rooms with floor area of 7.8 m² area and maintenance (light loss) factor of 0.67 are used. Light loss factor is the product of several factors including dirt of the environment, lamp depreciation over time, lamp burnout, reflector degradation, voltage instabilities, etc. which contribute to the depreciation of the light output in future as compared to the initial light output. It is assumed that these offices are on the first floor of a two-story building, supposedly located in Kuala Lumpur on latitude 3.04 ° North and longitude 101.79 ° East. Room 1 is at the corner of the building with a single window of 1 m (L) × 1 m (W); while room 2 is located in the middle of the building without a window. An active daylighting system consisting of 2S-NISC and optical fibers [9, 10] is proposed to be positioned on the rooftop of the building to illuminate room 2. The 2S-NISC concentrates sunlight to a receiver via a two-stage mirror reflector. The receiver are bundles of plastic optical fibers (POF) that transports the concentrated sunlight to room 2 for illumination.

LEDs are fixed on the ceiling of both rooms to compensate the lights coming into the room from the window or the 2S-NISC. A free lighting design software called DIALux 4.13 is used to design the room and to analyze the illuminance and energy savings in the room. DIALux 4.13 is a user friendly software that can be used to design, to evaluate and to professionally visualize light for single rooms, whole floors, buildings and outdoor scenes [11]. DIALux software performs daylighting simulation under three sky conditions: clear sky (with direct sunlight), mixed sky and overcast sky. All sky conditions are considered in this theoretical study for room 1 and room 2. The direct normal irradiance (DNI), global solar irradiance (GSI) and diffused solar irradiance (DSI) were previously measured with a pyranometer and pyrheliometer on 14th December, 2016 when the sky was clear (less than 30 % cloud covering), mixed (about 30 % to 70 % cloud covering) and overcast (100 % cloud covering) as shown in Table 1.
To analyze the illuminance and power savings in both office rooms, three different conditions were considered:

**Condition A**: Illuminance contributed from LEDs (all LED are switched on) for either room 1 (window closed) and room 2 (no window).

**Condition B**: Illuminance contributed from passive daylighting via window for room 1 and from active daylighting system via 2S-NISC for room 2 under clear, mixed and overcast sky conditions.

**Condition C**: Illuminance contributed from passive daylighting via window with compensation by LEDs in control groups for room 1 and from active daylighting system with compensation by LEDs in control groups for room 2 under clear, mixed and overcast sky conditions in order to achieve the required average illuminance of 500 lux.

### Table 1. DNI, GSI AND DSI measurements taken on the 14th of December 2016

| SKY CONDITION | Time (pm) | DNI (W/m²) | GSI (W/m²) | DSI (W/m²) |
|---------------|-----------|------------|------------|------------|
| Clear sky     | 2:16      | 887.79     | 1131.39    | 243.6      |
| Mixed sky     | 2:50      | 473        | 946        | 473        |
| Overcast sky  | 6:59      | 0          | 0          | 0          |

Based on the measured DNI, the expected illuminance in the room from the active daylighting system can be calculated with the analytical formula in comparison with the illuminance obtained from the simulation in DIALux [9]:

\[
I_{\text{Illuminance}} = \left( (C_{avg} - 1)R_{\text{facet}}^2 + 1 \right) \times I \times \%VL \times (1 - L_{\text{fiber}}) \times T_{HM} \times E_L \times \frac{A_{\text{fiber}}}{A_{\text{illum}}} \times N_{\text{fiber}}
\]

(1)

where \( C_{avg} \) symbolizes the average solar concentration ratio within uniform illumination area of concentrated flux (76 suns); \( R_{\text{facet}} \) symbolizes the reflectivities of the primary and secondary reflectors (93.5 %); \( I \) symbolizes the DNI only (W/m²); \( \%VL \) symbolizes the proportion of visible light within the whole solar spectrum in percentage (47 %); \( L_{\text{fiber}} \) symbolizes the overall optical loss of sunlight transmitting through a 10 m length of POF (45.7 %); \( T_{HM} \) symbolizes the transmission percentage of hot mirror accounted for visible range relative to full solar spectrum (98 %); \( E_L \) symbolizes the average direct beam luminous efficacy (104 lm/W); \( A_{\text{fiber}} \) symbolizes cross-sectional area of the POF (\( \pi \times 1.5^2 \) mm²); \( A_{\text{illum}} \) symbolizes the indoor illumination area (7.8 m²) and \( N_{\text{fiber}} \) symbolizes the number of POFs (314 fibers). From the 2S-NISC design, it was found that 314 POFs of 3 mm diameter each and 10 m length can give average illuminance of 500 lux to empty room with floor area of 7.8 m² without considering the room height [9].

### 2.1. Simulation set-up and room design in DIALux 4.13.

The dimensions of the office room modelled in DIALux are shown in Fig. 1 where N and E represents North and East respectively. In room 1, the window is located 0.9 m above the floor and 0.883 m from the left. The height of the working plane from the floor is 0.760 m in both rooms. The reflection factor for all the surfaces and objects in both rooms are as follows: all walls (78 %); floor (49 %); ceiling (78 %); door (88 %); office chair (64 %); window glass (6 %); office table (54 %), monitor with keyboard (53 %); CPU (50 %); book shelf (30 %); sofa (62 %) and paper basket (40 %). The transparency and mirror effect of the window glass are 90 % and 60 % respectively. The selected luminaire for the office room is Fraen Corporation FDP-M1-D01-HS-FDP medium white with a Platinum Dragon White LED lamp. Each LED lamp has a luminous flux of 100 lm and power of 1 W. To achieve illuminance of 500 lux in the 7.8 m² room, 60 luminaries with a dimension of 0.02 m (L) × 0.02 m (W) × 0.02 m (H) were used for the simulation. All LED’s were surface-mounted in the room ceiling, 2 m above the work plane as shown in Figure 2. For Condition A, no control groups were set for the luminaries. For Condition C, control groups were set for all luminaries to be able to control the dimming values of the lamps to save...
energy during the day. Luminaries in a control group are connected together and controlled with one switch in real life application. For room 2, the POFs are evenly arranged in between LEDs on the ceiling of the office room as illustrated in Figure 2. One bundle of POF consists of 7 strands of POFs and three bundles were placed together at specific locations on the ceiling for even distribution of light in the room.

Fig. 1. Office room design using DAILux 4.13 (left). Layout plan of luminaries and optical fibers on the ceiling of the office room – Luminaires are installed in rooms 1 and 2 and optical fibers are installed in room 2 only (right).

3. RESULTS AND DISCUSSION: Daylight performance and power saving analysis using DIALux 4.13

Table 2 presents the average illuminance, specific connected load and the power savings from DIALux 4.13 software simulation on office rooms 1 and 2 under conditions A, B and C.

Table 2. Illuminance on the working plane, specific connected load and power saved in room 1 and room 2 on 14th December, 2016.

| Condition | Room 1 – Windows + LED’s integration system |
|-----------|---------------------------------------------|
| Condition A – 60 LED’s only in either room 1 or 2 | Average room illuminance \( E_{av} \) = 519 lux, Specific connected load \( S_{cl} \) = 7.69 W/m² |
| Sky condition | Clear sky | Mixed sky | Overcast sky |
| Condition B: Illuminance from window only | \( E_{av} = 203 \) lux | \( E_{av} = 269 \) lux | \( E_{av} = 8.09 \) lux |
| Illuminance from LEDs needed for compensation to achieve 500 lux | \( E_{av} = 297 \) lux (from 37 LEDs) | \( E_{av} = 231 \) lux (from 30 LED’s) | \( E_{av} = 491.91 \) lux (from 58 LED’s) |
4. Conclusion

Theoretical analyses to study the illuminance distribution and power savings for the designs of two office rooms using DIALux 4.13 have been carried out for the 14th of December 2016. Room 1 consists of a combination of passive daylighting system and LEDs while room 2 has a combination of active daylighting system and LEDs to provide indoor room illuminance. The simulation results for the case of room 1 have shown that average illuminance of 203 lux, 269 lux and 8.09 lux can be achieved through only windows for the weather conditions of clear sky, mixed sky and overcast sky respectively; in which
power savings of 23 W (40.6 %), 30 W (53.8 %) and 2 W (1.62 %) can be achieved respectively. For the case of room 2, the simulation results using the formula obtained in Chong et al, 2017 [9] have shown that the 2S-NISC active daylighting system can produce average illuminance of 400 lux and 207 lux for the conditions of clear and mixed sky in a particular selected day in which power savings of 45 W (80 %) and 24 W (41.4 %) can be achieved respectively. The simulation result showed that higher illuminance and thus more power savings is obtained from the 2S-NISC in the case of room 2 as compared to the illuminance from the windows only in the case of room 1. The contribution of window towards daylighting is influenced by location, orientation of window and sky condition which can vary significantly at different times of the day. On the other hand, the contribution of active daylighting via the 2S-NISC system do not have these limitations and is applicable for room without windows regardless of their position in the building. Both the active and passive daylighting systems in this study have proven effective for power savings and can thus be applied in real life applications. In the early stages of a building’s design process, building professionals can apply this comprehensive and quick method to analyze the impact of active and passive daylighting in rooms towards reduction in electrical power consumption for lighting to achieve the purpose of energy savings. It is economically feasible and very affordable especially for the passive daylighting combination.

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References
[1] International Energy Agency (IEA). 25 Energy policy recommendations. France; 2011
[2] ‘Energy and the Environment Explained – Greenhouse gases’ Effect on the Climate’ U.S. Energy Information Administration. Updated: January 28, 2016
[3] Ihm P, Nemri A and Krarti M 2009. Estimation of lighting energy savings from daylighting Build. and Environ. 44, pp. 509-514
[4] Osama abed el-Raouf M, Mallawany A, Moasaad MI, Al-Ahmar MA and El Bendary FM 2018. Int. J. of Advances in Scientific Research and Engineering (ijasre) vol 4, pp. 79-88
[5] Shishegar N and Boubekri M 2017. Quantifying electrical energy savings in offices through installing daylight responsive control systems in hot climates Energy and Build. 153, pp. 87-98
[6] Kristensen PE 1994 Daylighting Technologies in Non-Domestic Buildings Int. J. Sol Energy, 15 pp 55-67. https://doi.org/10.1080/01425919408909822
[7] Zheludev N 2007 The life and times of the LED- a 100-year history Nat. Photonics 1, pp 189-192
[8] Liu KS, Chen JL, Huang CF and Chen YC 2014. Effects of different window treatments on energy saving and light control design J. Environ. Protect. and Ecology 15; nr. 3A
[9] Chong KK, Onubogu NO, Yew TK, Wong C and Tan W 2017 Design and construction of active daylighting system using two-stage non-imaging solar concentrator Appl. Energy 207, pp 45-60. https://doi.org/10.1016/j.apenergy.2017.05.188
[10] Obianuju ON and Chong KK 2017 High acceptance angle optical fiber based daylighting system using two-stage reflective non-imaging dish concentrator Energy Procedia 105, pp 498 – 504. https://doi.org/10.1016/j.egypro.2017.03.347
[11] https://www.dial.de/en/dialux/