Daylight-Adaptive Lighting Control Techniques: A Comparative Analysis of Particle Swarm Optimization and Firefly Algorithm

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***Abstract*—Lighting in commercial buildings consumes a substantial amount of energy. Therefore, this paper developed particle swarm optimization (PSO) and firefly algorithm (FA) as control techniques for lighting systems to improve energy efficiency and satisfy occupants' visual comfort in an indoor environment. An office room was considered to test the performance of the PSO and FA techniques. The proposed methods showed superior performance in minimizing the cost of energy consumption by more than 60% while satisfying illuminance-based metrics mentioned by the European Standard EN 12464-1. Based on the comparative result, PSO outperformed FA by 3% in energy savings. Due to its performance, the proposed PSO method can be utilized for other types of buildings.**

Keywords*—Daylight-adaptive control, energy efficiency, firefly algorithm, particle swarm optimization, optimization-based control.

I. Introduction

Energy consumption from lighting in commercial buildings is 18% in Malaysia, which is the second largest after air conditioning [1], as presented in Fig. 1. It has been reflected in higher greenhouse gas (GHG) emissions, where the prominent energy generation in Malaysia uses fossil fuels. Therefore, the implementation of energy-efficient strategies is required to improve energy performance and, at the same time, maintain the visual comfort of occupants. The energy-efficient strategies include (1) retrofitting the fluorescent lamps to light-emitting diode (LED) lamps, (2) occupancy-based control, and (3) daylight-linked control [2].

The daylight-linked control system has three main components: (i) light sensors (measure illuminance values), a controller (calculate the intensity level of lamps based on light sensor values), and dimmers (as an interface between the controller and luminaires). LED lamps are widely used in commercial buildings due to higher energy savings and long lifetimes. Moreover, LEDs have a special benefit for control purposes, which is the dimming level is proportional to the power consumption (minimize dimming level, minimize power consumption also) [3]. Illuminance is a main parameter that represents the amount of light (in lumens) in a space or area (in square meters) from light sources, i.e., artificial light and natural light (daylight). Thus, illuminance uniformity (U_o) and maintained illuminance level (E_m) are two illuminance-based metrics to represent occupants' visual comfort. The European Standard EN 12464-1 [4] includes these metrics. Based on the standard, for offices, the values of E_m and U_o are 500 lux and 0.6, respectively.

Three categories of lighting control strategies: (1) Conventional, (2) predictive and expert systems, and (3) optimization-based [3]. For conventional control, proportional integral (PI) [5] and proportional integral differential (PID) [6] are widely used. Artificial neural networks (ANNs) [7] is considered as a predictive control and fuzzy logic control (FLC) [8] is considered as an expert system control.

The optimization-based method is widely used due to its flexibility and performance (in terms of the optimal solution). Conventional and meta-heuristic are considered optimization-based methods. For conventional-based methods, research works utilized linear programming (LP)

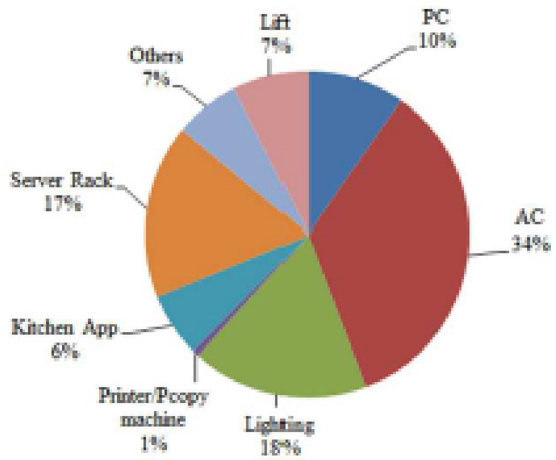

Fig. 1. Energy consumption in a commercial building [1].

[9]. Meta-heuristic methods are widely used in building energy systems, including particle firefly algorithm (FA) [1], swarm optimization (PSO) [2], and genetic algorithm (GA) [3]. In terms of lighting control, meta-heuristic methods have been implemented by researchers, such as modified competition over resources (COR) [10] and particle swarm optimization (PSO) [11]. The meta-heuristic methods have several advantages, such as solving non-linear problems and providing optimal solutions. For these reasons, this paper proposes two meta-heuristic methods as control techniques for lighting systems in a building, i.e., PSO and firefly algorithm (FA). The present research focuses on analyzing the performance of the optimal solution for both techniques while satisfying the occupants' visual comfort. The outperform method can improve the energy efficiency of the lighting system.

In the next section, the methodology is discussed (Section 2). Followed by Section 3, simulation results and discussion, and the final section is the conclusion (Section 4).

II. Methodology

The overall research methodology in this paper is presented in Fig. 2. Based on the figure, the research starts with model and simulate lighting system for both artificial lighting and daylighting using DIALux software. DIALux software was utilized in this research for simulating lighting systems. DIALux is a powerful lighting design and simulation software and widely used for designers and researchers around the globe. The parameters setting including E_{avg}, U_o and surface reflection factors were satisfied the EN 12464-1. The detailed parameters in DIALux are as follows: number of measurement points are 108 (9 × 12); working plane height is 75 cm; working hours are 8 am – 5 pm; and sky condition is clear. From the simulation results, illuminance model was developed based on Eq. (1).

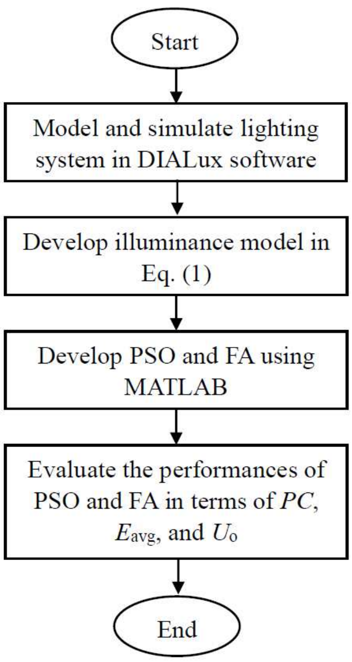

Fig. 2. Overall research methodology.

A. Illuminance Model

The total illuminance values ($\boldsymbol{E}_{total}(t)$) in an indoor space are represented by a combination of illuminances from daylighting ($\boldsymbol{E}_{dl}(t)$) (the first term of matrix) and artificial lighting ($\boldsymbol{E}_{al}$) (the second term of matrix) as formulated in Eq. (1). The values have been measured on the working plane.

$$E_{Total}(t) = \begin{bmatrix} E_{1,1} & \cdots & E_{1,n} \\ \vdots & \ddots & \vdots \\ E_{m,1} & \cdots & E_{m,n} \end{bmatrix} = \begin{bmatrix} E_{1,1} & \cdots & E_{1,n} \\ \vdots & \ddots & \vdots \\ E_{m,1} & \cdots & E_{m,n} \end{bmatrix} + d \begin{bmatrix} E_{1,1} & \cdots & E_{1,n} \\ \vdots & \ddots & \vdots \\ E_{m,1} & \cdots & E_{m,n} \end{bmatrix};$$

$$\text{where } d = \begin{bmatrix} d_1 \\ \vdots \\ d_i \end{bmatrix} \quad (1)$$

where m and n are the position of measurement points; d_i is ith zone of the dimming level of luminaires, which is calculated by control algorithm, such as fuzzy logic, particle swarm optimization, etc. The value of d_i is range of 0 (off) to 1 (full intensity) of light.

From Eq. (1), the average illuminance level (E_{avg}) and illuminance uniformity (U_o) can be determined. E_{avg} and U_o can be calculated as follow:

$$E_{avg} = avg[E_{Total}(t)] \quad (2)$$

$$U_o = \frac{E_{min}}{E_{avg}} \quad (3)$$

where E_{min} is the minimum illuminance value of $\boldsymbol{E}_{Total}(t)$.

B. Problem Formulation

The objective of the optimization-based method is to improve energy savings of lighting by minimizing dimming levels of LED lamps, while satisfying illuminance-based visual comfort. The objective function (FC) and constraints are formulated as:

$$\text{Min } F_C = \sum_{i=1}^{K} d_i \quad (4)$$

Subject to:

$$0 \leq d_i \leq 1 \quad (5)$$

$$E_{avg} \geq E_m \quad (6)$$

$$U_o \geq U_{o,min} \quad (7)$$

where Em and the minimum illuminance uniformity ($U_{o,\min}$) are refer to the standard.

To calculate power consumption (PC), Eq. (8) can be used:

$$PC = \sum_{i=1}^{K} (d_i \times P_{T,i}) \quad (8)$$

where $P_{T,i}$ is the total power of luminaires at ith zone (in kW).

C. Particle Swarm Optimization

Kennedy and Eberhart [12] was invented the particle swarm optimization (PSO). It is a population-based method and was motivated by the social behavior of animals. Animal group members are referred to as particles and the entire group as a swarm. In the beginning, a search space's particle positions are determined at random. The velocity is updated continually until gbest (global best position), which is the ideal solution, is obtained. The particles move from one point to another based on the set velocity. The new velocity (v(t+1)) and position (x(t+1)) update processes are:

$$v^{(t+1)} = iw \bullet v^{(t)} + a_1 b_1 (pbest^{(t)} - x^{(t)}) + a_2 b_2 (gbest^{(t)} - x^{(t)}) \quad (9)$$

$$x^{(t+1)} = x^{(t)} + v^{(t+1)} \quad (10)$$

where v(t) is the current velocity of the particles; $pbest^{(t)}$ and $gbest^{(t)}$ are the local and global best positions, respectively; $x^{(t)}$ is the current positions of the particles; b_1 and b_2 are [0,1] of random numbers; and a_1 and a_2 are acceleration constants.

A linear decreasing inertia weight method can improve the algorithm's performance in terms of fast convergence, in Eq. (11):

$$iw = iw_{\max} - \left(\frac{iw_{\max} - iw_{\min}}{ite_{\max}}\right) \times ite_j \quad (11)$$

where itemax and ite_j are the maximum and current iteration numbers, respectively. $iw_{\max}$ and $iw_{\min}$ are the maximum and minimum values of inertia weight, respectively.

MATLAB was utilized to develop the PSO algorithm. The parameters setting are as follows: $ite_{\max}$ = 100; $iw_{\max}$ = 0.9; $iw_{\min}$ = 0.4; c_1 and c_1 = 2; particle numbers = 20 and dimension = 12.

D. Firefly Algorithm

Yang [13] firstly developed the firefly algorithm (FA). FA is a meta-heuristic method that is inspired by the flashing behavior of fireflies and was inspired by the way that fireflies naturally attract partners or prey by flashing their lights. Three rules are considered in FA: (i) All fireflies consider as unisex, only a single firefly is attracted to other fireflies, (ii) the attractive and brightness is related, the most attractive firefly has higher brightness, (iii) the objective function will be determined by the brightness firefly.

Two crucial criteria in FA are light intensity and attractiveness. The light intensity *l(q)* of firefly with distance can be calculated as follows:

$$l(q) = l_0 e^{-\gamma q^2} \quad (12)$$

where γ is the light absorption coefficient, *q* is the distance between two fireflies and l_0 is the original light intensity.

The formulation of the firefly attractiveness *β(q)* as in Eq (13).

$$\beta(q) = \beta_0 e^{-\gamma q^2} \quad (13)$$

where β0 is the original attractiveness at q = 0.

To determine the distance between fireflies, Eq. (14) can be used.

$$q_{ij} = \|x_i - x_j\| = \sqrt{\sum_{s=1}^{d} (x_{i,k} - x_{j,k})^2} \quad (14)$$

The movement of fireflies towards an optimal solution can be computed in Eq. (15).

$$x_i^{t+1} = x_i^t + \beta_0 e^{-\gamma q^2}(x_j^t - x_i^t) + \alpha_t \varepsilon_t^t \quad (15)$$

where x_i^{t+1} and x_i^t are the new and current positions of the *i*th firefly, respectively, αt is a scaling parameter, and ε_t^t is a random numbers vector.

In this research, MATLAB was utilized to develop the FA algorithm. The parameters setting are as follows: the firefly numbers and dimension are the same with PSO; α = 0.3; β = 0.1 and γ = 1.

III. Results and Discussion

A. Case Study

The control strategies were implemented in an office room with 8 m (W) × 20 m (L) × 2.7 m (H) of dimension [14]. The room is installed with 35 LED lighting fixtures and the specifications per lamp are as follows: rated power of 34 W and luminous flux of 3,500 lumen. The layout of the room and assigned control zones are illustrated in Fig. 3.

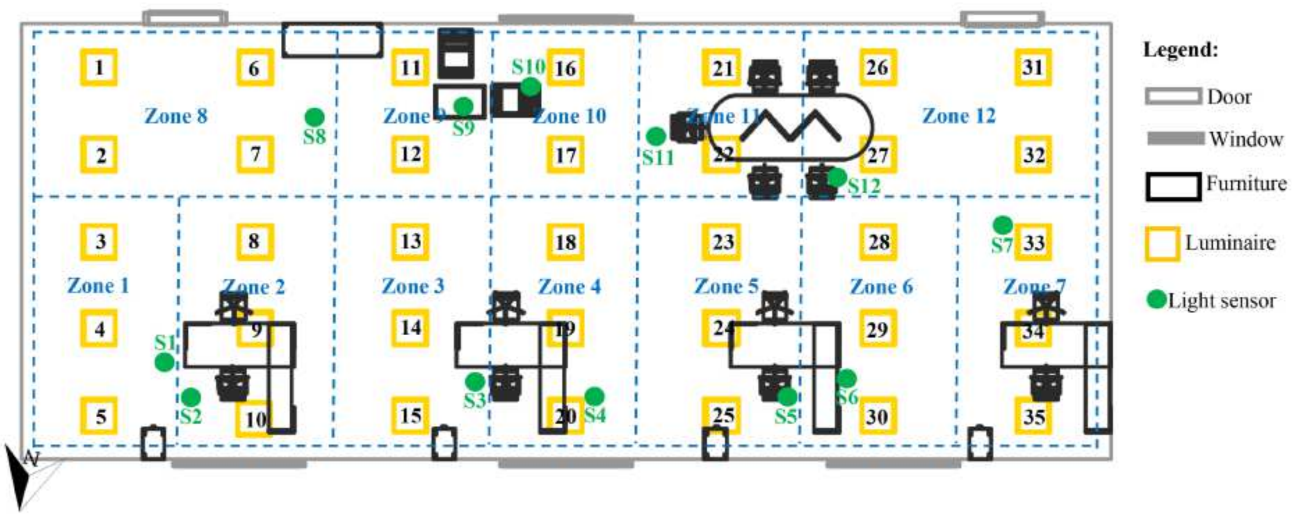

Fig. 3. Layout of the room [14].

TABLE I. PSO AND FA RESULTS FOR SELECTED TIMES.

Result	PSO							FA						
	8 am	9 am	10 am	12 pm	2 pm	4 pm	5 pm	8 am	9 am	10 am	12 pm	2 pm	4 pm	5 pm
d_1	0.54	0.40	0.47	0.46	0.45	0.27	0.27	0.46	0.53	0.52	0.62	0.40	0.25	0.19
d_2	0.34	0.18	0.08	0.11	0.03	0.05	0.00	0.46	0.14	0.09	0.08	0.12	0.07	0.01
d_3	0.39	0.14	0.26	0.26	0.26	0.26	0.26	0.83	0.25	0.26	0.26	0.15	0.11	0.12
d_4	0.48	0.07	0.01	0.00	0.00	0.00	0.08	0.43	0.11	0.05	0.19	0.06	0.04	0.15
d_5	0.26	0.02	0.36	0.33	0.27	0.27	0.27	0.23	0.13	0.21	0.28	0.26	0.31	0.12
d_6	0.14	0.28	0.10	0.07	0.08	0.04	0.04	0.15	0.08	0.04	0.18	0.14	0.21	0.09
d_7	0.48	0.63	0.60	0.63	0.68	0.68	0.61	0.42	0.53	0.64	0.67	0.72	0.65	0.58
d_8	0.87	0.55	0.60	0.63	0.66	0.56	0.47	0.60	0.81	0.80	0.63	0.57	0.52	0.57
d_9	0.38	0.45	0.49	0.46	0.38	0.38	0.23	0.44	0.28	0.52	0.46	0.51	0.34	0.17
d_{10}	0.00	0.00	0.03	0.04	0.00	0.04	0.07	0.04	0.09	0.09	0.02	0.10	0.04	0.03
d_{11}	0.26	0.37	0.25	0.37	0.49	0.38	0.37	0.14	0.20	0.43	0.60	0.52	0.37	0.47
d_{12}	0.88	0.46	0.61	0.71	0.61	0.64	0.51	0.86	0.72	0.52	0.58	0.61	0.66	0.61
$\sum d$	5.02	3.53	3.85	4.07	3.92	3.57	3.19	5.05	3.86	4.18	4.56	4.16	3.57	3.10
PC (kW)	0.55	0.37	0.41	0.43	0.41	0.38	0.34	0.54	0.43	0.44	0.47	0.43	0.38	0.33
E_{avg}	501	516	575	575	572	580	521	500	547	589	596	579	582	519
U_o	0.63	0.60	0.60	0.60	0.61	0.60	0.60	0.61	0.61	0.60	0.60	0.60	0.60	0.61

B. *Simulation Results*

In this section, the simulation results of the PSO and FA optimization-based control strategies are presented. Moreover, the comparison results of baseline, PSO and FA are also presented.

a) PSO and FA Optimization-based Controls: Table 1 shows the PSO and FA optimization-based control strategies in terms of d_i, $\sum d_i$, PC, Eavg and U_o. Based on the table, both control techniques were satisfied the illuminance-based visual comfort (i.e., E_m and U_o). By referring to the EN 12464-1, the targeted E_m and U_o are 500 lux and 0.6, respectively.

b) Comparison results of the PSO and FA: In this case, a baseline (no dimming control) for working hours of 11.9 kW for the total *PC* and it is based on hourly *PC* of 1.19 kW (35 luminaires × 34 W). Fig. 2 shows the comparison of *PC* by the baseline, PSO and FA for working hours. Based on the figure, the proposed techniques significantly reduced the *PC*. The highest *PC* was about 0.55 kW at 8.00 am for both methods. At this time, the illuminance level from daylight was lowest compared to others time. As a result, the room required more lumens to satisfy E_{avg} and U_o (Eqs. (2) and (3)) that reflecting to higher *PC*. The lowest *PC* was around 0.33 kW for both techniques. The U_o at this time was higher (illuminance levels more uniform) compared to others time. Thus, more zones of luminaires consumed low power consequently lower *PC*. In overall performance, it clearly showed that PSO method was lower *PC* compared to the FA method.

The total energy savings throughout working hours are illustrated in Fig. 3. By referring to the figure, the proposed methods achieved more than 60% energy savings. When considering 20 working days per month and 12 month per year, and RM 0.365 electricity tariff for commercial building (C1), the annual energy savings of PSO and FA control techniques were RM 685.00 and RM 659.80, respectively. It can be seen that PSO technique outperformed FA technique by 3%.

IV. CONCLUSION

The goal of optimization-based lighting control is to improve energy performance of lighting, while satisfying illuminance-based metrics (visual comfort). This paper proposes two meta-heuristics, i.e., PSO and FA as control techniques in lighting systems. The proposed control strategies were implemented in an office room. The proposed methods improved energy savings greater than 60% as comparison to the baseline. The comparative analysis showed that PSO outperformed FA by 3%. PSO method showed great performance and can be implemented to other type of buildings. In future, the hybridization of PSO and FA can be proposed to achieve great results in terms of optimal solutions in lighting control systems.

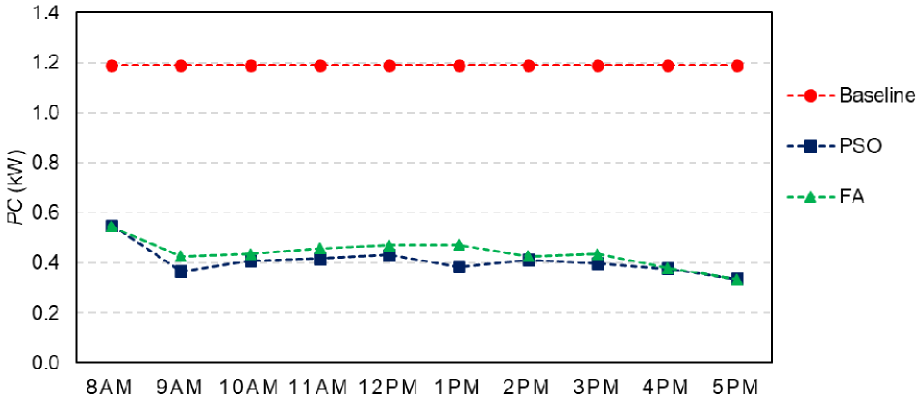

Fig. 4. Comparison of *PC* by the baseline, PSO and FA for 8 am to 5 pm.

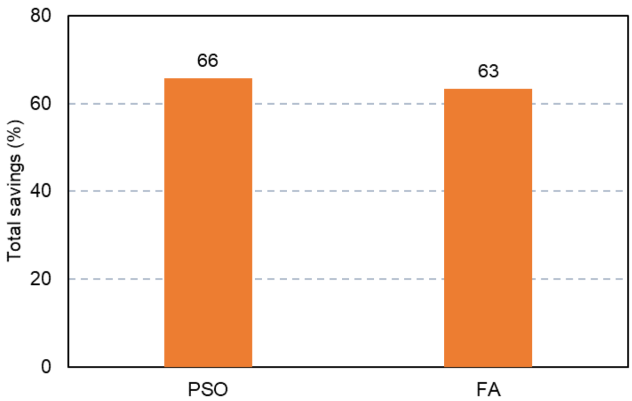

Fig. 5. Comparison of the total *EC* savings between PSO and FA for working hours.

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