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Research on energy-saving lighting control of high-rise building by the PID control algorithm

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Abstract. The lighting of high-rise buildings consumes a significant amount of electricity, making it essential to implement energy-saving measures. In this paper, the lighting of high-rise buildings was briefly analyzed, followed by a description of the proportion, integration, and differentiation (PID) control algorithm. To improve the efficiency of lighting control for energy conservation, the fuzzy PID control algorithm was analyzed. The self-tuning of parameters was achieved by utilizing the whale optimization algorithm (WOA) to develop a WOA-fuzzy PID control algorithm. Finally, experimental analysis was carried out. The simulation findings showed that the WOA-fuzzy PID algorithm had the shortest stabilization time (6.77 s), the smallest maximum overshoot (3.12%), and better anti-interference capability compared to the PID and fuzzy PID algorithms. Finally, it was found from practical application that the use of the WOA-optimized algorithm resulted in a 43.7% reduction in monthly electricity consumption. The findings suggest the effectiveness of the WOA-fuzzy PID algorithm in energy-efficient lighting control and its applicability to real-world high-rise buildings.

Keywords: High-rise building / lighting control / LED lamp / energy-saving / PID control algorithm

1 Introduction

With the accelerated progressing in both economy and society, the issue of energy saving is becoming prominent [1]. There is a significant amount of energy waste in different fields. Therefore, how to save energy and how to maximize the energy utilization rate is always a challenge [2]. Due to the demand of housing for social development, the real estate industry continues to expand, and the quantity of high-rise buildings is experiencing an increase [3]. In the overall energy usage of society, a significant portion is attributed to building energy consumption [4], and lighting energy consumption is one of its main components [5]. Most of the current buildings employ manual lighting control, leading to unnecessary high light level and considerable energy inefficiency. If real-time adjustment of lamp light output is implemented based on task illuminance, energy could be effectively saved.

Energy-saving control of the lighting system has been widely studied. Sun et al. [6] put forward an indoor lighting control approach based on a framework to control lamps and window blinds. They demonstrated the intelligence of the method through computer simulation experiments. Futagami et al. [7] introduced a progressive lighting control approach using motion sensors, which can dim the light levels of the fixtures above the occupants in light of daylight availability for daylight harvesting. They evaluated the potential of that approach for reducing energy use while enhancing occupants' comfort. Farkas et al. [8] investigated the energy-saving control of outdoor lighting systems based on power line communication (PLC) technology to achieve energy savings and reduce operation and maintenance costs. Cesari et al. [9] analyzed the influence of the window size and glazing type in buildings on electric lighting use. They found that using broader windows with suitable glazing, along with a specific dimming strategy of the electric lighting, resulted in a significant reduction of approximately 17% in primary energy consumption.

In this paper, a lighting control approach based on an improved proportion, integration, and differentiation (PID) control algorithm was designed for the energy-efficient lighting of high-rise buildings. This approach integrates the traditional PID control algorithm with fuzzy logic to fuzzify the parameters and utilizes the whale optimization algorithm (WOA) for self-tuning of these parameters, thereby further improving the control performance. The effectiveness of the approach in energy saving was proven by experimental analysis. This paper provides a novel approach for lighting control in high-rise buildings and offers some theoretical support for implementing the PID control algorithm in other lighting systems.

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Table 1. Standard values for office building lighting.

Room or place	Standard value of illuminance (lx)	Color rendering index
General office	300	80
Upscale office	500	80
Meeting room	300	80
Video meeting room	750	80
Reception room, front desk	200	80
Service hall, business hall	300	80
Design studio	500	80
Document sorting, copying, and distribution room	300	80
Storage room for materials and files	200	80

Table 2. Comparison of incandescent, fluorescent, high-pressure sodium, and LED lamps.

	Incandescent lamp	Fluorescent lamp	High-pressure sodium lamp	LED lamps
Luminous efficacy (lm/W)	16	70–90	110–135	80–150
Color temperature (K)	2,400–2,900	3,800	1,900–2,800	4,500–6,000
Color rendering index	95–99	60–90	23 to 25	75–80
Life span (h)	1,000–2,000	8,000–15,000	20,000–28,000	50,000

2 Materials and methods

2.1 Analysis of lighting in high-rise building

In the current high-rise building, the traditional lighting control method, mostly manual control, is predominantly used. Under manual control, the lighting equipment is regularly switched on or off, and the brightness is kept consistent. In this case, users often forget to turn off the lights. In addition, in the case of good natural light conditions, it becomes impossible to adjust the brightness, resulting in a significant waste of energy. The most crucial aspect of energy-saving lighting control is to regulate light brightness based on real-time illuminance measured by the light sensor to minimize lighting energy consumption. Compared with traditional lighting control, energy-saving lighting control offers the following advantages.

- Energy-saving: Lighting brightness is adjusted according to the changes in natural light to achieve energy savings.
- Prolonging the lifespan of lamps: The lifespan of lamps is linked to the length of time they are illuminated. By implementing energy-saving lighting controls, the duration of lighting can be shortened, thereby extending the lifespan of the lamps.

At present, various algorithms are commonly used for controlling energy-saving lighting, including classical control algorithms (such as PID), reinforcement learning methods, neural network methods, and others [10]. This paper mainly studied the PID control algorithm. Taking a high-rise office building project in Jiangsu Province as an example, the building is 92 m meters tall, comprising 19 floors, including three podium floors and three underground floors, and its energy-saving lighting control was analyzed.

First of all, according to the "Standard for Lighting Design of Buildings" (GB50034-2013), the lighting standard requirements for high-rise office buildings are presented in Table 1.

According to the actual situation, the most prevalent room in this high-rise office building was the general office; therefore, this paper primarily focuses on studying the energy-saving lighting control algorithm for general offices. When selecting lamps, the commonly used lighting sources are listed in Table 2.

In Table 2, LED lamps exhibit significantly superior luminous efficacy compared to incandescent and fluorescent lamps, as well as high color temperature and color rendering index. Additionally, their service life is sufficient for practical applications. Therefore, this paper used LED lamps as the lighting source for the high-rise office building. The dimming methods of LED lamps are as follows.

- Segmented switch dimming: LED lamps are divided into different groups. By turning on and off different groups of LED lamps, all on, partial on, and all off are realized.
- Analog linear dimming: By adjusting the resistance of the adjustable resistor, the operating current of LED lamps is altered.
- Pulse-width modulation (PWM) dimming: Dimming is achieved by adjusting the average output current.

PWM dimming offers the advantages of swift response and exceptional dimming accuracy [11]. Therefore, PWM dimming technology was used in this study, and the

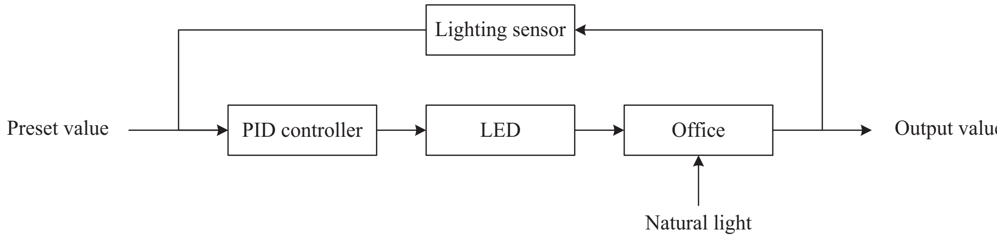

Fig. 1. Energy saving lighting control scheme based on PWM dimming and PID control.

specific scheme is shown in Figure 1. The actual illuminance of the office under natural light was obtained using the illumination sensor and compared with the preset value. The LED dimming was achieved by utilizing the PID control algorithm to generate PWM dimming signals.

2.2 PID control algorithm

The PID algorithm is a very common algorithm [12] with simple principle and good control effect, which has been widely employed in the industrial field [13]. Assuming that the preset value of the system is $r(t)$ and the actual output value of the controlled object is $y(t)$. The deviation is:

$$e(t) = r(t) - y(t).$$

The output of PID is:

$$u(t) = K_p\left[e(t) + \frac{1}{T_1}\int e(t) + T_D\frac{de(t)}{dt}\right], \tag{1}$$

where K_p stands for the proportionality coefficient, T_I stands for the integration time constant, and T_D represents the differential time constant.

The transfer function of PID is expressed as:

$$G(s) = K_p + \frac{K_I}{s} + K_D s, \tag{2}$$

where K_I stands for the integral coefficient, $K_I K_I = K_p / T_I$, and K_D denotes the differential coefficient, $K_D = K_p / T_D$.

When PID is applied to digital control signal, it first needs to be discretized to obtain digital PID. In this paper, incremental PID [14] was used, and the PID after discretization at time k is written as:

$$u(k) = K_p \times e(k) + K_i T \sum\nolimits_{j=0}^{k} e(j) + K_d \frac{e(k) - e(k+1)}{T}. \tag{3}$$

The incremental PID control algorithm can be obtained by $u(k) - u(k-1)$:

$$\Delta u(k) = K_p \times [e(k) - e(k-1)] + K_i T_e(k) + \frac{K_d[e(k) - 2e(k-1) + e(k-2)]}{T}, \tag{4}$$

where $e(k)$, $e(k-1)$, and $e(k-2)$ refer to the system deviation value at time k, k–1, and $k-2$.

2.2.1 Fuzzy PID control algorithm

The PID control algorithm requires parameter reconfiguration for each tuning session, lacking automatic adjustment capability, which can impact the overall effectiveness of energy-saving lighting control. Therefore, expert experience is incorporated into fuzzy reasoning to achieve the adjustment of PID parameters, resulting in the fuzzy PID control algorithm [15].

Compared with PID, fuzzy PID fuzzifies all parameters in PID by fuzzy method and takes deviation e between the actual illuminance and the preset illuminance obtained by the lighting sensor and deviation change rate ec as the input. According to the standard value of illuminance in ordinary offices, the fuzzy domain of e is set as [–300,300], and its basic domain is [–3,3]; the fuzzy domain of ec is [–100,100], and its basic domain is [–3,3]. Seven fuzzy subsets are used to represent the input and output parameters of PID:

$$\{NB, NM, NS, ZO, PS, PM, PB\},$$

which are corresponding to negative large, negative medium, negative small, zero, positive small, positive medium, and positive large.

Given the extensive computational requirements, the input and output of PID use triangular membership function [16], which has good resolution and high sensitivity. Then, in terms of fuzzy rules, considering the stability and overshoot of the system, it is appropriate to increase K_p and K_d and decrease K_i in the initial stage, and then decrease K_p and K_d and increase K_i in the middle and late stages to obtain better steady-state accuracy. Finally, the fuzzy rules for energy-saving lighting control are shown in Table 3.

The output obtained after fuzzy reasoning needs to be defuzzified. In this paper, the centroid approach was used:

$$v_o = \frac{\int \mu_j \cdot \mu_B(\mu_j) dv}{\int \mu_B(\mu_j) dv}, \tag{5}$$

where $\mu_B(\mu j)$ is the membership degree when the input is μ_j.

After defuzzification, the actual parameters of PID can be obtained:

$$\begin{cases} K_p = K_{p0} + \Delta K_p \\ K_i = K_{i0} + \Delta K_i \\ K_d = K_{d0} + \Delta K_d \end{cases} \tag{6}$$

where K_{po}, K_{io}, and K_{do} represent a set of initial PID parameters determined by trial and error.

2.2.2 Whale optimization algorithm

In fuzzy PID control, the proportionality factor and quantization factor are generally determined based on experience and may need to be readjusted when the operating conditions change. In order to achieve self-tuning of parameters, this paper introduced the WOA [17] to improve the fuzzy PID control algorithm and develop the WOA-fuzzy PID control algorithm.

First, the location of the whole population is initialized:

$$X_i = lb + rand \times (ub - lb), \tag{7}$$

where ub and lb indicate the upper and lower boundaries of of the search space and $r\,and$ indicates a random numerical value between 0 and 1.

WOA uses three steps to hunt prey, that is, to find the optimal solution, as follows.

(1) Hunting

Let the best whale position be $X^*(t)$ and the position of the other whales be $X_i(t)$. Then, the other whales move closer to the best position, which can be written as:

$$D = |C{\cdot}X^*(t) - X_i(t)|, \tag{8}$$

$$X_i(t+1) = X^*(t) - A{\cdot}D, \tag{9}$$

$$A = 2ar - a, \tag{10}$$

$$C = 2r, \tag{11}$$

$$a = 2 \times \left(1 - \frac{t}{T}\right), \tag{12}$$

where $X_i(t+1)$ stands for the search location of the ith whale at the $t+1$-th time of iteration, D is the distance between the current position and the best position, A and C are random parameters, r is a random number in [0,1], t and T are the current and maximum count of iterations.

(2) Bubble net attack

Whales engage in bubble predation using including contraction encircling and spiral encircling. The probability of whales choosing either of these two methods is 50%. The details of the two methods are as follows:

① contraction encircling: similar to hunting, and $a = 2 - \frac{2t}{T}$;

② spiral encircling: $X_i(t+1) = |X^*(t) - X_i(t)|e^{bl} \cdot \cos(2\pi l) + X^*(t)$,

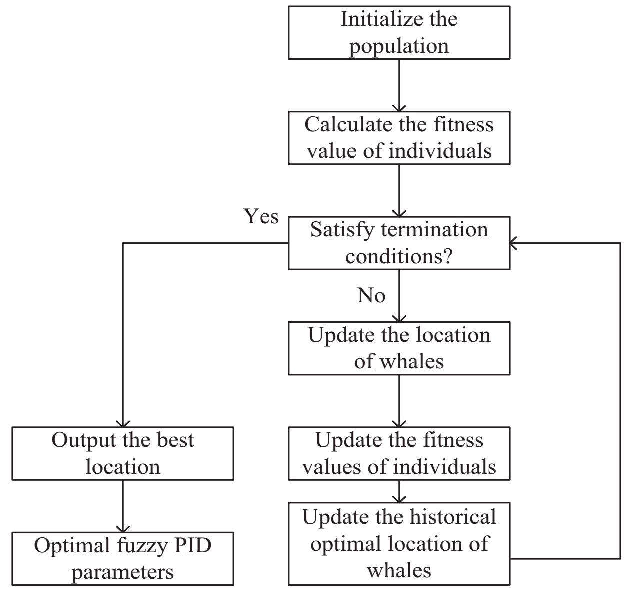

Fig. 2. The flowchart of optimizing the fuzzy PID parameter by the WOA.

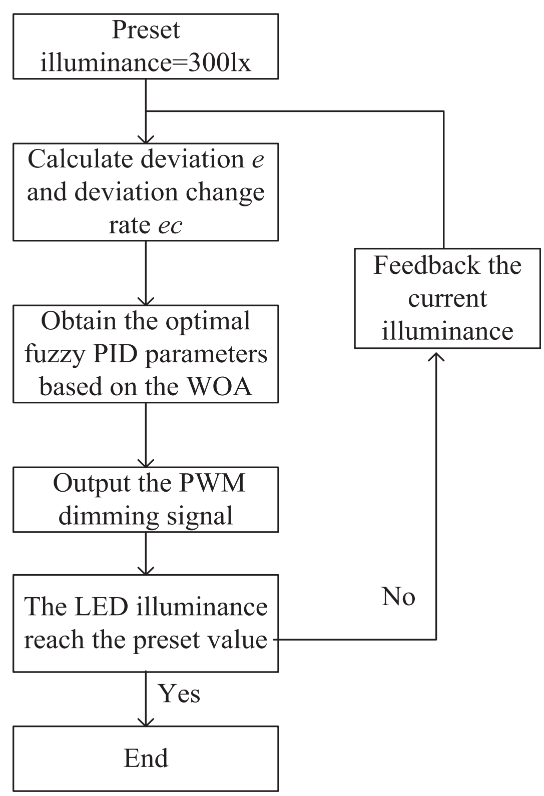

Fig. 3. The flowchart of the energy-saving illumination control based on the WOA-fuzzy PID control algorithm.

where b indicates logarithmic spiral shape constant and l is a random number in [–1,1].

(3) Random search

Table 3. Fuzzy rules of ΔK_p, ΔK_i, and ΔK_d.

ec	e						
	NB	*NM*	*NS*	*ZO*	*PS*	*PM*	*PB*
NB	PB/ZO/PB	PB/PB/PM	PB/PB/PS	PB/PS/PS	PM/PM/ZO	PM/PS/PM	PS/ZO/PB
NM	PB/ZO/PS	PB/PM/PM	PB/PM/PS	PM/PM/PS	PM/PS/ZO	PS/PS/PS	ZO/ZO/PS
NS	PM/ZO/NS	PM/PS/NM	PM/PM/NS	PS/PS/ZO	ZO/ZO/ZO	ZO/ZO/PS	ZO/ZO/PS
ZO	PS/ZO/NM	PS/ZP/NM	ZO/PS/NS	ZO/ZO/ZO	ZO/NS/NM	NS/ZO/PS	NS/ZO/PM
PS	PS/ZO/NM	ZO/ZO/NM	ZO/ZO/ZO	ZO/NM/ZO	NS/NM/PS	NM/ZO/PM	NM/ZO/PM
PM	PS/ZO/NS	ZO/NS/NS	NS/NS/PS	NS/NM/PS	NM/NM/PS	NB/NM/PM	NB/ZO/PS
PB	PS/ZO/NS	ZO/NS/ZO	NS/NS/PS	NS/NB/PS	NB/NB/PM	NB/NB/PB	NB/ZO/PB

Table 4. Test functions for algorithm optimization performance.

Function	Dimension	Range	Minimum
$f_1(x) = \sum_{i=1}^{n} x_i^2$	30	[–100,100]	0
$f_2(x) = \sum_{i=1}^{n} \lvert x_i \rvert + \prod_{i=1}^{n} \lvert x_i \rvert$	30	[–10,10]	0
$f_3(x) = \sum_{i=1}^{n} \left(\sum_{j=1}^{i} x_j \right)^2$	30	[–100,100]	0
$f_4(x) = max_i\{\lvert x_i \rvert, 1 \leq i \leq n\}$	30	[–100,100]	0
$f_5(x) = \sum_{i=1}^{n-1} \left[100\left(x_{i+1} - x_i^2\right)^2 + (x_i - 1)^2 \right]$	30	[–30,30]	0

When individuals are far away from the best position, they will use random search to get closer to enhance the capability of global search. The formulas are written as:

$$X_i(t+1) = Xr\ and(t) - A \cdot D, \tag{13}$$

$$D = |C \cdot Xr\ and(t) - X_i(t)|, \tag{14}$$

where $Xr\ and\ (t)$ is the current random individual position and D stands for the distance between the current random individual and the best position.

Figure 2 shows the process of obtaining the optimal fuzzy PID parameters using the WOA.

Figure 3 illustrates the flowchart of the WOA-fuzzy PID control algorithm.

– The illuminance of the general office is preset to be 300 lx, and deviation e and deviation change rate ec are obtained by comparing it with the actual illuminance of the light sensor.
– The WOA population is initialized, and the fitness is calculated: $f_{ITAE} = \int_0^\infty t|e(t)|d_t$, where f_{ITAE} stands for integral time absolute error [18].
– Whether the termination condition is satisfied is determined. If the condition for termination is satisfied, the optimal fuzzy PID parameters are output. If not, the next step is initiated.
– The position of the whale is continuously updated using the WOA, and the fitness value is calculated until the optimal parameters are found.
– The PWM dimming signal outputted by the PID controller is transmitted to the LED lamp to achieve dimming.

(3) Experiments and results

Firstly, the optimization performance of the WOA was analyzed. It was compared with the particle swarm optimization (PSO) and grey wolf optimization (GWO) algorithms using five unimodal benchmark functions. Table 4 shows these functions.

Table 5. Optimization results of the PSO algorithm, GWO algorithm, and WOA for five functions.

	PSO	GWO	WOA
f_1	4.514	1.872e-62	0
f_2	3.565	4.595e-36	0
$f3$	1205.254	1.357e-20	0
f_4	1.568	1.321	0
f_5	133.658	25.254	26.577

Each algorithm was repeated 30 times independently. The optimal values obtained by these algorithms are shown in Table 5.

It can be found from Table 5 that the WOA obtained the optimal values when optimizing f_1 - f_4, suggesting significantly better performance compared to the PSO and GWO algorithms. The results revealed that the WOA had better convergence precision and speed, as well as a robust optimization capacity. Therefore, the selection of the WOA for fuzzy PID parameter optimization was dependable.

To assess the usability of the proposed approach for energy-saving lighting control in general offices, PID, fuzzy PID, and WOA-fuzzy PID control models were developed using the Simulink model in MATLAB. The simulation results are illustrated in Figure 4.

Based on Figure 4, the performance of different models was compared in Table 6.

Combining Figure 4 and Table 6, it can be found that the PID model required the longest stabilization time, tending to stabilize after 12.37 s. In contrast, the fuzzy PID model had a stabilization time of 8.62 s, which was 30.32% shorter than that of the PID model. After optimization by the WOA, the WOA-fuzzy PID model achieved the shortest stabilization time of 6.77 s. This time was 45.27% shorter than that of the PID model and 21.35% shorter than the fuzzy PID model. These results suggested that the WOA-fuzzy PID model had a good response speed.

The maximum overshoot refers to the maximum deviation from the target value that a system experiences after reaching the target value, expressed as a percentage. The comparison of the maximum overshoots indicated that the maximum overshoot of the PID model was the highest, which was 13.87%, followed by the fuzzy PID model at 11.24%. The maximum overshoot of the WOA-fuzzy PID model was the smallest, at only 3.12%, which was 10.75% lower than that of the PID model and 8.12% lower than that of the fuzzy PID model. Through comparison, it can be found that under the same conditions, the WOA-fuzzy PID model had a shorter stabilization time and lower overshoot, suggesting a superior control effect.

To determine the interference effect of the model, an interference signal was added at $t = 20$ s, and the simulation results are presented in Figure 5.

From Figure 5, it can be found that after adding the interference signal, the system under PID control exhibited two oscillations, indicating poor anti-interference ability, while the systems under the fuzzy PID and WOA-fuzzy PID models showed only one oscillation. In comparison, the time required for the WOA fuzzy PID model to restore the steady state was shorter, indicating that its anti-interference ability was better than that of the fuzzy PID model. These results demonstrate the reliability of enhancing the fuzzy PID model by incorporating WOA.

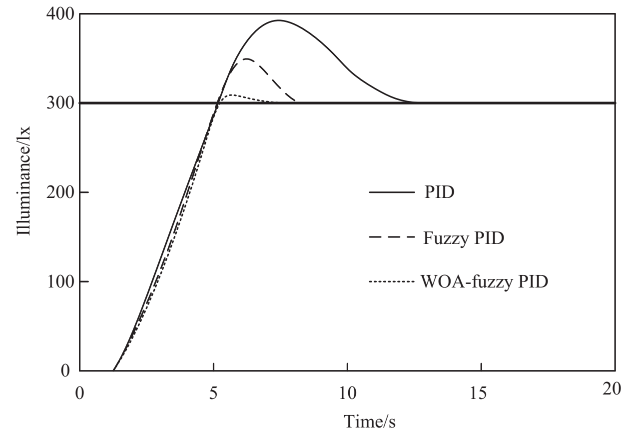

Fig. 4. Simulation results of the PID, fuzzy PID, and WOA-fuzzy PID models for energy-saving lighting control.

Table 6. Comparison of stabilization time and maximum overshoot between different models.

	PID	Fuzzy PID	WOA-fuzzy PID
Stabilization time/s	12.37	8.62	6.77
Maximum overshoot /%	13.87	11.24	3.12

Ten ordinary offices with similar natural light levels in the high-rise building under investigation were chosen for the experiment. Each office had the same area, and an equal number of LED lamps were installed in identical positions in these offices. Five of them were used as Group A for traditional lighting control, where the lamps were controlled by a switch, and the brightness was not adjustable. Additionally, five rooms were designated as Group B for energy-saving lighting control, utilizing the WOA-fuzzy PID algorithm. The test period lasted from 8:00 to 17:00 and ran continuously for one month. The results are displayed in Table 7.

Table 7 shows that under the traditional lighting control, the average indoor illuminance was consistently high at 500 lx, indicating excessive lighting, and the monthly electricity consumption reached 40.34 kWh. Under the WOA-fuzzy PID algorithm, the average indoor illuminance was 312 lx, meeting the requirements of GB50034-2013. The monthly electricity consumption was 22.71 kWh, which was 43.7% less than that of Group A. These results demonstrate the effectiveness of the WOA-fuzzy PID algorithm in energy-saving lighting control.

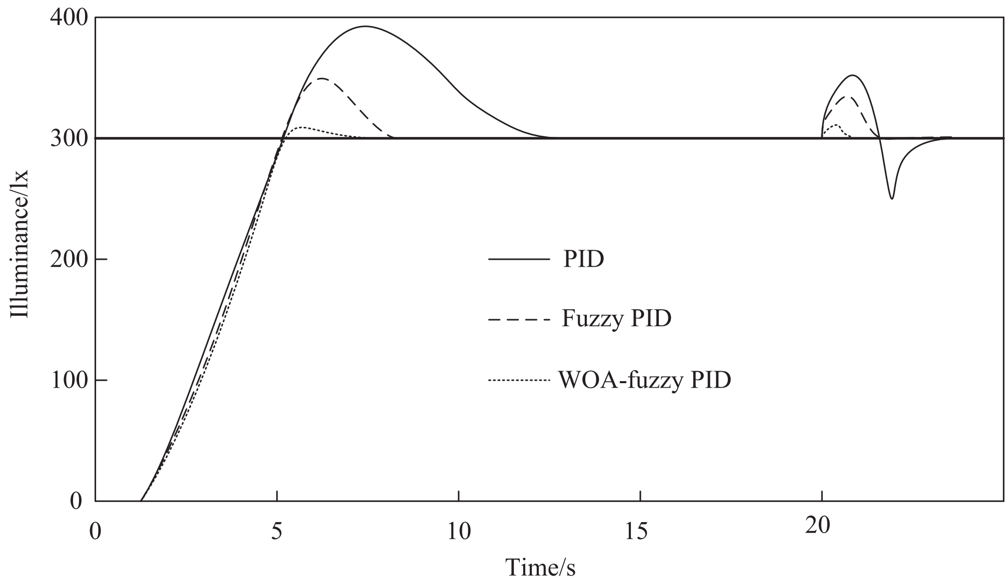

Fig. 5. Anti-jamming simulation results of the PID, fuzzy PID, and WOA-fuzzy PID models.

Table 7. Comparison between the actual application results of the WOA-fuzzy PID algorithm and the traditional lighting control results.

	Group A	Group B
Monthly electricity consumption/kWh	40.34	22.71
Average indoor illuminance/lx	500	312

4 Discussion and conclusion

The lighting of high-rise buildings consumes a significant amount of energy, making it an increasingly important focus in energy-saving research. The reliability of LED lighting in terms of energy efficiency has been demonstrated through the results of 52 pilot projects by Omran et al. [19]. Barkhordar's study [20] also confirms the significant role played by LED lights in energy-saving illumination. Therefore, this paper investigated the control of energy-saving lighting in high-rise buildings using LED lights.

The advancement of intelligent algorithms has enabled the possibility of achieving intelligent control of lighting. Liu et al. [21] utilized genetic algorithms to achieve optimal illumination compensation in dark environments, thereby realizing intelligent light compensation. Yi et al. [22] developed a Bluetooth-based smart lighting controller that enables switch control, brightness adjustment, and various lighting mode transformations through Bluetooth connectivity. Li et al. [23] proposed an intelligent method for illuminance measurement based on binocular stereoscopic vision, allowing for dynamic monitoring and control of illuminance. From current research, it is evident that intelligent lighting control has been extensively studied. However, there is limited discussion regarding the energy-saving effects of intelligent lighting control and even fewer studies focusing on high-rise buildings as a whole. Therefore, this paper specifically analyzed the energy-saving situation in ordinary offices located in high-rise buildings within the context of intelligent lighting control. By combining the fuzzy PID algorithm with the WOA, parameter optimization was achieved to further enhance the algorithm's control performance. The results showed that the WOA was a robust optimization algorithm that demonstrates consistent performance in fuzzy PID parameter optimization. The simulation findings indicated that, compared to the PID and fuzzy PID algorithms, the WOA-fuzzy PID algorithm demonstrated a faster response and smaller overshoot, proving its effectiveness in light control in terms of speed and accuracy. Lastly, the application results indicated that when using this algorithm for energy-saving lighting control, it reduced monthly electricity consumption by 43.7% while still meeting the preset illuminance requirements.

The experimental results demonstrate the effectiveness of the approach proposed in this paper for energy-saving lighting control in high-rise buildings. This approach can be implemented in real office spaces within high-rise buildings and can help reduce building energy consumption. However, there are some limitations in this study. For example, the experimental time was relatively short during practical application experiments, and there are also many other areas in high-rise buildings with different illuminance requirements. In future research, it is necessary to simulate more complex lighting scenarios in high-rise buildings to further validate the applicability of the approach proposed in this paper.

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Conflict of interest

The authors have nothing to disclose.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author contribution statement

Conceptualization, Qiong Yang; Methodology, Zixuan Yue; Software, Zixuan Yue; Validation, Qiong Yang; Formal Analysis, Zixuan Yue; Investigation, Qiong Yang; Resources, Zixuan Yue; Data Curation, Zixuan Yue; Writing-Original Draft Preparation, Qiong Yang; Writing-Review & Editing, Qiong Yang; Visualization, Zixuan Yue; Supervision, Qiong Yang; Project Administration, Qiong Yang; Funding Acquisition, Zixuan Yue.

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