Fade Lighting Control Method for Visual Comfort and Energy Saving

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Abstract

This study proposes a fade lighting control method to ensure the visual comfort of indoor occupants through gradual illuminance control while saving energy. The illuminance sensor measures the indoor illuminance and calculates the required illuminance for achieving a reference illuminance of 500 Lux. The control illuminance for each lighting is derived based on the required illuminance, and it is confirmed to fall within the threshold range of 20%. The illuminance values and time intervals for fade lighting control are calculated, ensuring that the amount of illuminance adjustment is divided by the size of the threshold range or less. In the performance evaluation, the proposed method (experimental group) was compared with the influence-based control method (control group). The result shows that this fade lighting control method minimizes the visual discomfort of occupants caused by sudden changes in lighting, and the same energy-saving of 11-42% is achieved as the control group.

Keywords: fade lighting control, visual comfort, multiple lighting, energy saving

1. Introduction

Modern people spend most of their time indoors, leading to an increase in energy consumption of indoor lighting [1-3]. To reduce this energy consumption, research has been conducted to introduce natural light into indoor lighting environments [4-5]. Furthermore, introducing natural light has been highly recommended due to its potential health benefits for occupants, especially in the workplace. It increases work productivity, reduces stress, and improves employee satisfaction. [6-7]. However, light levels could change rapidly depending on weather conditions; for instance, when the sun is covered by clouds [8-9]. In environments with a high concentration of large buildings, rapid changes in illuminance could also occur when the sun appears or disappears [10-12]. Therefore, to maintain the indoor reference illuminance according to the purpose of the lighting, rapid illuminance changes are inevitable.

Rapid changes in illuminance could cause the irises of occupants to contract or relax rapidly, resulting in visual discomfort and reduced work efficiency [13-15]. Various methods have been proposed to address the problems caused by drastic changes in lighting illuminance. Liu et al. [16] presented a deep q-network (DQN) algorithm-based control method for lighting illuminance that responds to human density and changes in natural light. Through deep reinforcement learning (DRL), the system calculates the best lighting mode, balancing comfort and energy efficiency. It dynamically adjusts to environmental changes, minimizing manual interventions. As a result, their DQN-based approach realized up to 62% power savings compared to conventional lighting systems. Kruisselbrink et al. [17] developed a method to regulate lighting according to indoor illuminance and natural light conditions. Algorithm 1 used proportional control, while Algorithm 2 chose from 13 predefined scenes. Every 30 seconds, the best scene is determined based on current illuminance. Notably, Algorithm 2 outperformed Algorithm 1 in achieving consistent illuminance and realized a significant 70% energy savings.

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Papinutto et al. [18] introduced a lighting control system that leverages machine learning (ML) to optimize the use of natural light and reduce energy consumption. The system maximizes daylight while using a task light to decrease the need for lighting, and it incorporates an automated strategy for blinds to prevent discomfort glare. This system's ML component accurately predicts key indicators such as work plane illuminance and daylight glare probability, facilitating real-time adjustments of blinds and electric lighting. The system achieves an energy saving of 35 Wh on average compared to manual room operations by users.

Previous studies have mostly proposed solutions to alleviate the visual discomfort of occupants via an excessive influx of natural light. However, there has been a lack of research on lighting control methods that respond to the rapidly changing natural light caused by weather conditions and the external environment, with the goal to mitigate the visual discomfort of the occupants.

This study proposed a fade lighting control method to address sudden changes in indoor illuminance, aiming to reduce visual discomfort for occupants and energy consumption. The fade lighting control method minimizes visual discomfort by gradually controlling the illuminance of the lighting within a threshold range (20% of the current illuminance) when a sudden change in illuminance occurs.

In this study, the illuminance sensor *(TSL 4531, ams AG, Austria)* was placed at various points in the room, and the indoor illuminance change was measured according to the inflow of natural light. The reference illuminance that the indoor lighting environment should maintain is 500 lux, which is in line with the recommended indoor illuminance of KS A 3011 standard, ranging from 300 to 600 lux [19-20]. Then, the control lighting was selected, and the control illuminance was derived through the influence-based lighting control algorithm for energy-saving. If the control illuminance of a lighting exceeds the threshold range, the illuminance of the lighting is gradually controlled by dividing the control illuminance and adjusting the time interval. This prevents sudden changes in indoor illuminance and minimizes the visual discomfort of occupants. The performance of the fade lighting control method was evaluated by comparing indoor illuminance and energy consumption with and without its application.

2. Fade Lighting Control Method

The proposed fade lighting control method gradually adjusted the illuminance of individual lighting within a specific threshold range to minimize the residents' ocular strain when sudden changes in indoor illuminance occur. Fig. 1 is a conceptual diagram of the fading lighting control method.

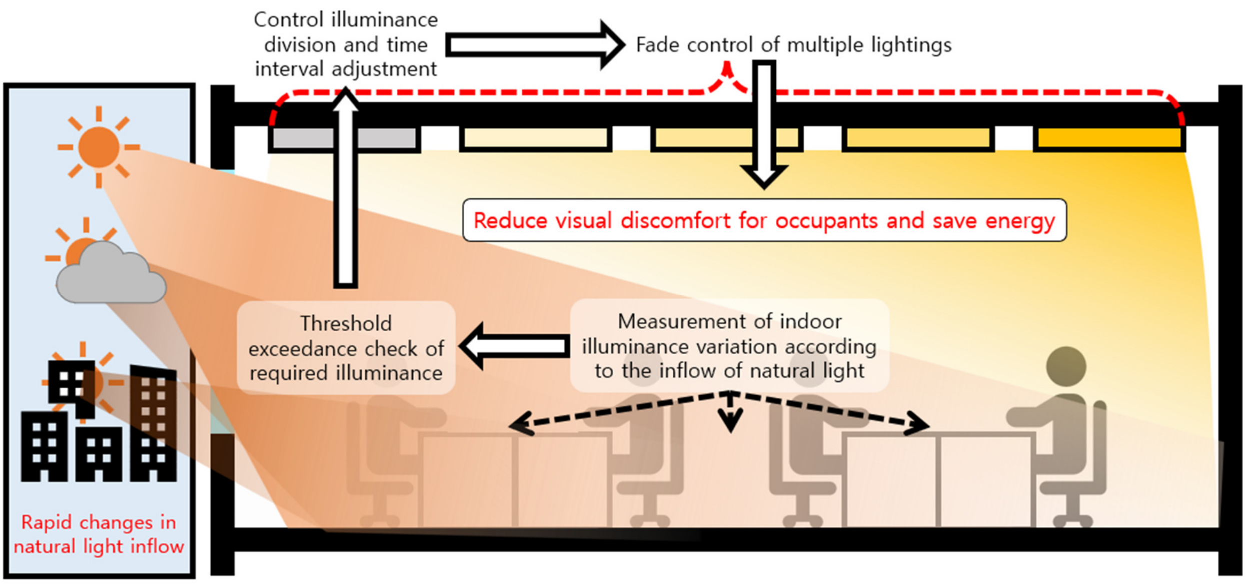

Fig. 1 Conceptual diagram of the fading lighting control method

As shown in Fig. 1, the fade lighting control method measured the illuminance changes at various points in the indoor space according to the amount of natural light inflow. The illuminance at each point was collected every second, and the average illuminance was calculated. The required illuminance to match the reference illuminance (500 lux) was calculated based on the indoor average illuminance. Subsequently, the calculated illuminance was checked to determine if it exceeded the threshold range. If the required illuminance exceeded the threshold range, the illuminance of the lighting was progressively managed by dividing the control illuminance and adjusting the time interval. Fig. 2 is a flowchart of the fade lighting control method.

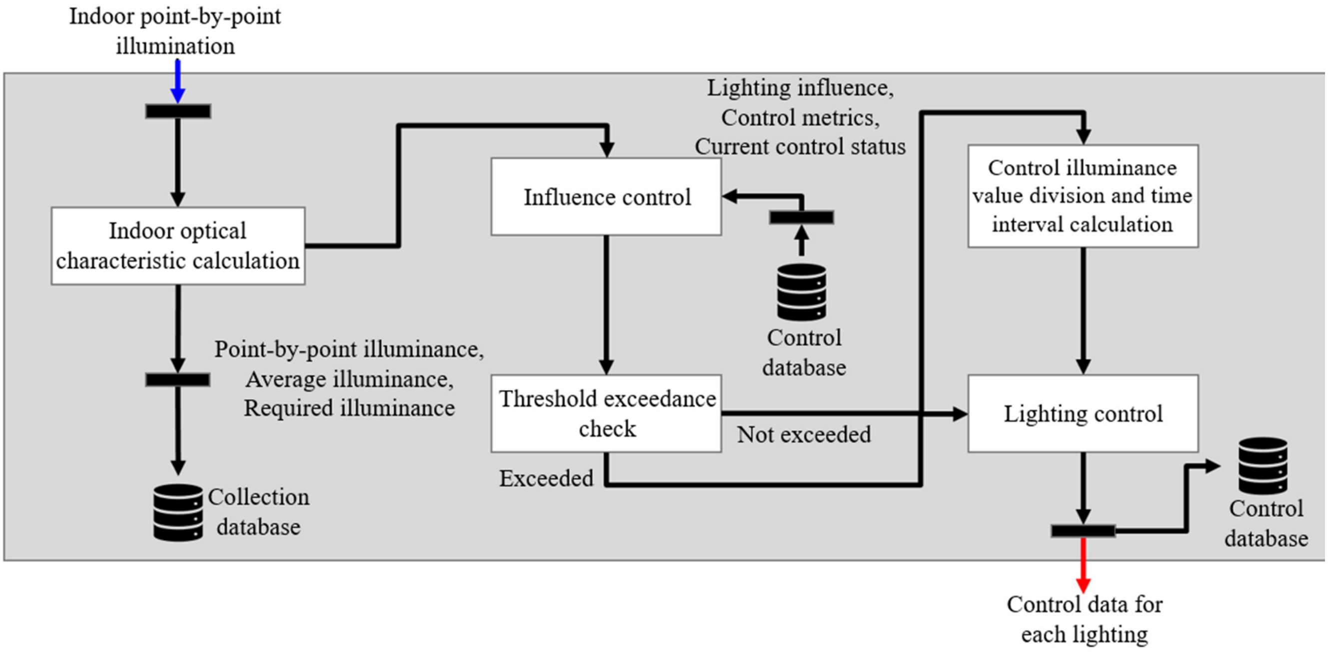

Fig. 2 Flowchart of the fade lighting control method

In the indoor optical characteristic calculation module in Fig. 2, the average illuminance and required illuminance were calculated from the point-by-point illuminance and stored in the collection database. In the influence control module, influence represents the contribution of illuminance that lighting makes to multiple points. Control lightings were selected based on their influence relative to the required illuminance. The control illuminance values of the selected lightings were then derived to fulfill the required illuminance. The threshold exceedance check module verified whether the control illuminance value of the lighting exceeded the threshold. If the control illuminance value was below the threshold, the channel-specific applied current value corresponding to the control illuminance value was sent to the lighting control module. If it was out of the threshold range, the control illuminance value was sent to the control illuminance value division and time interval calculation module.

The control illuminance value division and time interval calculation module divided the control illuminance value into threshold range sizes and set time intervals. After that, it sent the channel-specific applied current values corresponding to each partitioned control illuminance value to the lighting control module. The lighting control module controlled the lighting by sequentially transmitting the channel-specific applied current values at each time interval. This minimizes residents' visual discomfort while realizing energy savings in lighting. Fig. 3 depicts the pseudocode of the indoor optical characteristic calculation module.

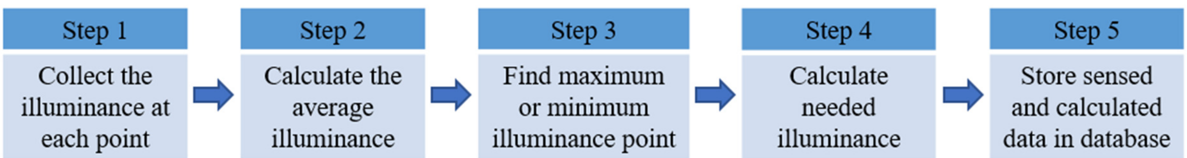

Fig. 3 Flow of the indoor optical characteristic calculation module

First, the indoor optical characteristic calculation module collected illuminance from sensing data measured at each point in the room according to the inflow of natural light. Next, the average illuminance ($Illum_{avg}$) of each point indoors ($Illum_x$) was calculated as:

$$Illum_{avg} = \frac{\sum_{x=1}^{n} Illum_x}{n} \tag{1}$$

Then, the maximum and minimum illuminance points were found from the illuminance at each point in the room. After that, the required illuminance($Illun_{need}$) for the average indoor illuminance to meet the reference illuminance($Illun_{std}$) can be found as:

$$Illum_{need} = Illum_{std} - Illum_{avg} \tag{2}$$

Fianlly, the sensed and calculated data were stored in the collection database. Where x is the number of the lightings in the n lightings.

The influence control module used influence-based lighting control algorithms to save energy [16]. Based on this, lighting control saves 11-42% more energy compared to the general lighting environment that provides a fixed illuminance [21]. Control points and lights were selected based on influence, and the required illuminance for each control light was calculated. For the average illuminance in the room to meet the reference illuminance, the required illuminance should be zero. To achieve this, the control illuminance value of the selected lights was calculated based on the influence level. To mitigate the visual discomfort of the occupants due to sudden changes in lighting, the control illuminance values of the lights were checked to see if they exceeded the threshold range. Fig. 4 shows the pseudocode of the threshold exceedance check module.

```
1: Calculate threshold rage illuminance
2: If control values > threshold range of illuminance
3:     Send control values to control illuminance value division and time interval calculation
4: else
5:     Send control values to lighting control
6: endif
```

Fig. 4 Pseudocode of the threshold exceedance check module

In line 1 of Fig. 4, the threshold range illuminance for each lighting was calculated. If the control illuminance value of the lighting exceeds the threshold range in line 2, the control illuminance value of the lighting is sent to the control illuminance division and time interval calculation module in line 3 to derive the illuminance value for each step of the fade lighting control. If the threshold range is not exceeded in line 2, the channel-specific applied current value corresponding to the controlled illuminance value of the lighting is sent to the lighting control module in line 5. Fig. 5 shows the pseudocode of the control illuminance value division and time interval calculation module.

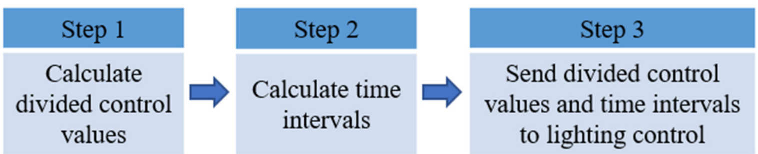

Fig. 5 Flow of the control illuminance value division and time interval calculation module

The calculation of the fade control illuminance value ($FadeCtrIllum_{(x,y)}$) in line 1 of Fig. 5 is obtained by

$$FadeCtrIllum_{x,y} = \left(CurrIllum_x + \sum_{z=0}^{y-1} FadeCtrIllum_{x,z} \right) \times 0.2 \tag{3}$$

$CurrIllum_{(x)}$ represents the current illuminance at point x, and the first control illuminance value with y=1 has no fade control illuminance value at step y-1; therefore, $FadeCtrIllum_{(x,0)}$ is set to 0. Each time a fade control illuminance value is generated, the number ($SegCount$) of steps in the fade control illuminance value is incremented by 1. This was repeated to create an array of fade control illuminance values. If the sum of the fade control illuminance values exceeds the required illuminance, the last value is removed. The remaining control illuminance value ($RestCtrIllum_{(x)}$) was then derived using:

$$RestCtrIllum_x = Illum_{need} - \sum_{z=0}^{SegCount-1} FadeCtrIllum_{x,z} \tag{4}$$

The remaining control illuminance was calculated by subtracting the sum of the $FadeCtrIllum_{(x,0)}$ from the required illuminance ($Illun_{need}$) to meet the room average illuminance. All controls could be completed within 60 seconds, and the fade control time interval can be calculated by:

$$FadeInterval = \frac{60}{SegCount} \tag{5}$$

$\lfloor \ \rfloor$ is an integer, discarding the decimal point. x is the number of lights in n lights, and y is the step number of the fade control illuminance value divided into m pieces.

The fade control illuminance values were divided by the magnitude of the threshold range illuminance values to make the room's average illuminance meet the reference illuminance while keeping the lighting control to a minimum. Subsequently, an array of channel-specific applied current values and time intervals corresponding to the divided fade control illuminance values were sent to the lighting control module. Fig. 6 shows the pseudocode of the lighting control module.

```
1: If control values is array
2:     for i = 0 to length of control values
3:         If curr time – prev time >= time interval
4:             Send control values[i] to lighting
5:         endif
6:     endfor
7: else
8:     Send control values to lighting
```

Fig. 6 Pseudocode of the lighting control module

As shown in Lines 1 and 7 of Fig. 6, the applied current values for each channel of the lightings were divided into two cases: fade control and one-step control within the threshold range. In the fade control case, lines 2 through 6 sequentially send the applied current value of the fade control to the lightings at each control interval ($FadeInterval$). For a single control within the threshold range, line 8 sends it directly to the lighting. This was to minimize the visual discomfort of the occupants in a situation of rapid illuminance change while satisfying the standard illuminance (500 Lux) and reducing the energy consumption of the lighting.

3. Experiment and Analysis

To evaluate the performance of the fade lighting control method proposed in this study, an experimental environment was constructed and an experiment with rapidly increasing and decreasing illuminance was organized. Fig. 7 shows the experimental environment.

The experimental environment had dimensions of 650 cm × 560 cm × 270 cm (width, length, height), and 30 LED lights (5 rows × 6 columns) were installed on the ceiling, each individually controllable. A wattmeter was installed at the power source of the lights to measure the power consumption of the lightings. Nine illuminance sensors were placed on the floor at a height of 85 cm from the floor surface according to the KS C 7612 illuminance measurement method. Subsequently, to compare the variations in illuminance and energy-saving performance resulting from the application of the proposed method, a control group utilizing an influence-based lighting control algorithm was established. Furthermore, an experimental group was formed by augmenting the control group's method with the proposed fade lighting control. The experiments were conducted under the assumption of rapid changes in indoor illuminance. Fig. 8 illustrates the outcomes of lighting control in scenarios where there is a sudden decrease in natural light influx, necessitating an increase in illuminance.

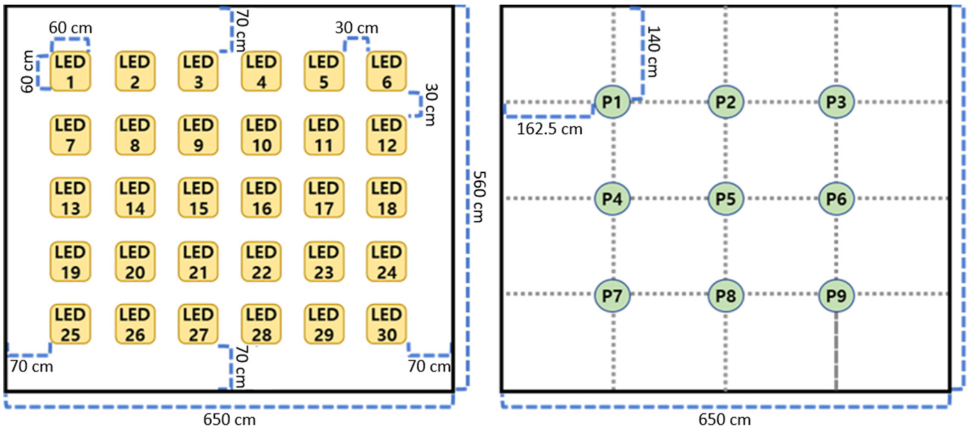

Fig. 7 Experimental environment

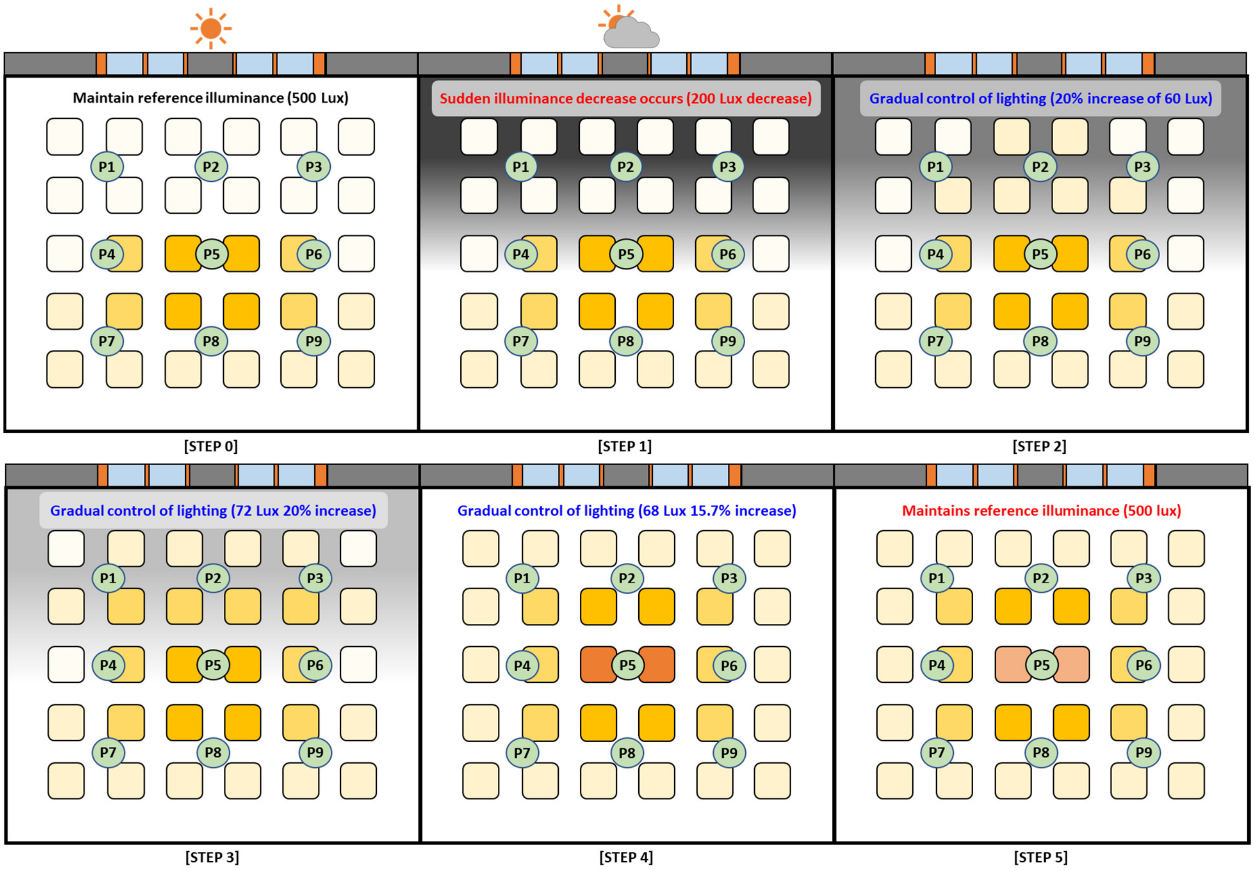

Fig. 8 Experiment where there was a sudden decrease in natural light inflow

3.1. *Experimental Condition 1: Increase the illuminance of the lighting*

Experiment 1 was set up in a situation where the sun was covered by clouds, reducing the incoming illuminance of natural light. The experimental group was controlled to gradually increase the illuminance of the light by applying the fade lighting control method as shown in Fig. 8. The control group was controlled to increase 200 lux (about 66.7% of the current illuminance) at a time in the STEP 1 situation.

Table 1 Result of Experiment 1

STEP	Average Illuminance (Lux)		Power (W)	
	Control Group	Experiment Group	Control Group	Experiment Group
STEP 0	500	500	71.17	71.17
STEP 1	300	300	71.17	71.17
STEP 2	500 (66.7% increase)	360 (20% increase)	106.24	81.69
STEP 3	500	432 (20% increase)	106.24	94.31
STEP 4	500	500 (15.7% increase)	106.24	106.24

In STEP 0 of Table 1, both the control and experimental groups started with an average illuminance of 500 Lux and a power consumption of 71.17W. In STEP 1, the sun is covered by clouds and the indoor illuminance decreases rapidly (200 lux). In STEP 2, the control group met the baseline illuminance (500 lux) by increasing 200 lux at a time. However, the sudden change in illuminance (about 66.7% of the current illuminance) caused glare to the occupants. This occurs frequently from sunrise to sunset on bad weather days, causing visual discomfort to the occupants. At this time, the control group consumed 106.24W of power due to the increased illuminance. The experimental group was controlled by gradually increasing the illuminance within the threshold range from STEP 2 to STEP 3. In STEP 4, the remaining illuminance was controlled to maintain the baseline illuminance. The energy of the experimental group gradually increased, and upon the completion of the control, it consumed the same power of 106.24W as the control group.

The power consumption (W) indicated in Table 1 represents the unit power consumption per unit of time, and the energy usage of the lighting corresponds to the consumption over a 1-hour period. In Steps 1 to 4, the control group consumed 1.62 Wh of power over 1 minute, while the experimental group consumed 1.47 Wh. As a result, the experimental group consumed 9.36% (0.15 Wh) less energy per minute for lighting compared to the control group.

Experiment 2 was set up in a situation where the sun came out of the clouds and the incoming illuminance of natural light was increased by 200 lux (40% of the existing illuminance), resulting in an average indoor illuminance of 700 lux. The experimental group was the opposite of Experiment 1, with a gradual decrease in illuminance. The control group was controlled to decrease 200 lux (28.6% of the current illuminance) at a time.

3.2. Experimental Condition 2: Decrease the illuminance of the lighting

Table 2 Result of Experiment 2

STEP	Average Illuminance (Lux)		Power (W)	
	Control Group	Experiment Group	Control Group	Experiment Group
STEP 0	500	500	106.24	106.24
STEP 1	700	700	106.24	106.24
STEP 2	500 (28.6% decrease)	560 (20% decrease)	71.17	81.69
STEP 3	500	500 (10.7% decrease)	71.17	71.17

In STEP 0 of Table 2, both the control and experimental groups started with an average illuminance of 500 Lux and a power consumption of 106.24W. In STEP 1, the sun came out of the clouds and the indoor illuminance increased rapidly (200 lux). In STEP 2, the control group maintained the baseline illuminance (500 lux) by reducing 200 lux of illuminance at a time. The experimental group was reduced to an illuminance level within the threshold range in STEP 2. In STEP 3, the baseline illuminance was maintained by controlling the remaining illuminance to achieve zero required illuminance. The energy of the experimental group was gradually reduced, and after the control was completed, the experimental group consumed 71.17W of power, the same as the control group.

From Step 1 to Step 3, the control group consumed 1.38 Wh of power over 1 minute, while the experimental group consumed 1.44 Wh. As a result, compared to the control group, the experimental group consumed 4.23% (0.06 Wh) more energy per minute for lighting. However, in Experiment 1, the experimental group consumed 0.09 Wh less energy than the control group, effectively achieving an additional energy saving of 0.05 Wh. On the other hand, the control group induced visual discomfort in occupants by implementing illuminance control beyond the threshold range; whereas the experimental group managed to both alleviate visual discomfort and achieve energy savings by maintaining control within the threshold range, consuming less energy compared to the control group.

4. Conclusions

In this study, a fade lighting control method is proposed to prevent sudden changes in lighting. This method involved measuring room illuminance changes and adjusting based on the intensity of natural light. The strategy revolved around an established control threshold (20% of current illuminance). If exceeded, the light control illuminance and time interval were adjusted.

To evaluate the performance of the proposed method, an environment with multiple lightings was set up, and illuminance and energy were measured. In two experiments, sudden decreases and increases in natural light were simulated. The control group made immediate adjustments, while the experimental group modulated illuminance gradually. The control group frequently experienced visual discomfort due to sudden changes, while the experimental group maintained changes within a comfortable range.

In Experiment 1, the experimental group consumed 0.09 Wh (9.36%) less energy per minute compared to the control group. In Experiment 2, the experimental group consumed 0.04 Wh (4.23%) more energy per minute than the control group. For the control group, the influence-based control method was applied, showing an energy-saving effect of 11-42% compared to conventional lighting environments with fixed illuminance. Additionally, the experimental group consumed 0.05 Wh less energy per minute than the control group. It is predicted that the energy-saving effect of the experimental group over the control group would increase further in scenarios where lighting variations continue due to unfavorable weather conditions. Thus, the proposed method minimized the visual discomfort of the occupants while reducing the energy of lighting by introducing natural light.

In the future, a real-time control system can be constructed with a fading lighting control method. Experiments can be conducted from sunrise to sunset under various weather conditions and seasons to validate the performance of the proposed method. This study has limitations as it conducted simulation experiments assuming rapid changes in indoor illumination. Ensuring the same level of performance throughout the entire day in real-world applications is uncertain. Therefore, the performance in real environments with varying weather conditions and levels of illumination changes offers the direction for future research.

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgments

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References

[1] J. Guo and Y. Zhang "Research on Control Method of Comfortable Lighting and Energy Saving Lighting," 2021 International Conference on Advanced Technology of Electrical Engineering and Energy, pp. 87-92, December 2021.
[2] F. Yilmaz, "Lighting Energy Performance Determination in Office Environments through Implementation of EN 15193-1 for Turkey," Lighting Research & Technology, vol. 53, no. 8, pp. 749-776, December 2021.

[3] E. Dolnikova, D. Katunsky, and M. Lopusniak, "Evaluation of Daylight Comfort in Industrial Building," IOP Conference Series: Materials Science and Engineering, vol. 1252, article no. 012031, 2022.
[4] A. M. Al-Ghaili, H. Kasim, N. M. Al-Hada, M. Othman, and M. A. Saleh, "A Review: Buildings Energy Savings - Lighting Systems Performance," IEEE Access, vol. 8, pp. 76108-76119, 2020.
[5] K. Mantzourani, L. T. Doulos, A. Kontadakis, and A. Tsangrassoulis, "The Effect of the Daylight Zone on Lighting Energy Savings," IOP Conference Series: Earth and Environmental Science, vol. 410, article no. 012099, January 2020.
[6] I. Turan, A. Chegut, D. Fink, and C. Reinhart, "The Value of Daylight in Office Spaces," Building and Environment, vol. 168, article no. 106503, January 2020.
[7] J. H. Jou, Z. K. He, D. K. Dubey, Y. F. Tsai, S. Sahoo, Y. T. Su, et al., "Approach for Designing Human-Centered and Energy Saving Lighting Luminaires," Photonics, vol. 9, no. 10, article no. 726, October 2022.
[8] C. Miao, S. Yu, Y. Hu, H. Zhang, X. He, and W. Chen, "Review of Methods Used to Estimate the Sky View Factor in Urban Street Canyons," Building and Environment, vol. 168, article no. 106497, January 2020.
[9] A. Tabadkani, A. Roetzel, H. X. Li, and A. Tsangrassoulis, "A Review of Occupant-Centric Control Strategies for Adaptive Facades," Automation in Construction, vol. 122, article no. 103464, February 2021.
[10] E. Rynska and M. Yanchuk, "Dense and Proximate Development—Daylight in the Downtown Area of a Compact City," Sustainability, vol. 14, no. 2, article no. 774, January 2022.
[11] M. Fakhari, R. Fayaz, and R. Lollini, "The Impact of Evaluated Daylight to the Total Light Ratio on the Comfort Level in Office Buildings," Buildings, vol. 12, no. 12, article no. 2161, December 2022.
[12] C. Moscoso, K. Chamilothori, J. Wienold, M. Andersen, and B. Matusiak, "Window Size Effects on Subjective Impressions of Daylit Spaces: Indoor Studies at High Latitudes Using Virtual Reality," LEUKOS, vol. 17, no. 3, pp. 242-264, 2021.
[13] A. Tabadkani, A. Roetzel, H. X. Li, and A. Tsangrassoulis, "Daylight in Buildings and Visual Comfort Evaluation: The Advantages and Limitations," Journal of Daylighting, vol. 8, no. 2, pp. 181-203, December 2021.
[14] S. Yeom, H. Kim, T. Hong, and M. Lee, "Determining the Optimal Window Size of Office Buildings Considering the Workers' Task Performance and the Building's Energy Consumption," Building and Environment, vol. 177, article no. 106872, June 2020.
[15] A. Montaser Koohsari and S. Heidari, "Optimizing Window Size by Integrating Energy and Lighting Analyses Considering Occupants' Visual Satisfaction," Built Environment Project and Asset Management, vol. 11, no. 4, pp. 673-686, 2021.
[16] J. Liu, H. M. Chen, S. Li, and S. Lin, "Adaptive and Energy-Saving Smart Lighting Control Based on Deep Q-Network Algorithm," 6th International Conference on Control, Robotics and Cybernetics, pp. 207-211, October 2021
[17] T. W. Kruisselbrink, R. Dangol, and E. J. van Loenen, "A Comparative Study between Two Algorithms for Luminance-Based Lighting Control," Energy and Buildings, vol. 228, article no. 110429, December 2020.
[18] M. Papinutto, R. Boghetti, M. Colombo, C. Basurto, K. Reutter, D. Lalanne, et al., "Saving Energy by Maximising Daylight and Minimising the Impact on Occupants: An Automatic Lighting System Approach," Energy and Buildings, vol. 268, article no. 112176, August 2022.
[19] I. Golasi, F. Salata, E. de L. Vollaro and A. Peña-García, "Influence of Lighting Colour Temperature on Indoor Thermal Perception: A Strategy to Save Energy from the HVAC Installations," Energy and Buildings, vol. 185, pp. 112-122, 2019
[20] H. Jeong, W. Kim, Y. Kim, H. J. Han, and W. Chun, "Electric Lighting Energy Saving Through the Use of A Fresnel Lens Based Fiber-Optic Solar Lighting System: Simulation and Measurements," Journal of the Korean Solar Energy Society, vol. 27, no. 3, pp. 1-12, June 2017. (In Korean)
[21] S. H. Lee, "Development of a Grid Lighting System that Saves Energy by Applying an Influence-Based Control Algorithm," Master thesis, Graduate School of Multimedia Engineering, Kongju National University, Cheonan, Korea, 2023.