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Development of a Dimming Lighting Control System Using General Illumination and Location-Awareness Technology

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Received: 29 September 2018; Accepted: 29 October 2018; Published: 1 November 2018

Abstract: As part of ongoing research into saving lighting energy, studies on lighting control integrating location-awareness technologies have recently been increasing, but these have led to the indoor illuminance imbalance problem by controlling only the lighting adjacent to the occupant. Therefore, the purpose of this study is to develop a dimming lighting control system using general illumination and location-awareness technology by integrating general illumination and dimming technology with lighting control technology that is based on location-recognition, and to verify the effectiveness of this system. This study built a full-scale test bed to evaluate the performance of the developed technology, and derived the energy reduction rate and indoor light environment improvement rate to evaluate the performance of dimming lighting control (Case 1), dimming lighting control using location-awareness technology (Case 2), and dimming lighting control using general illumination and location-awareness technology (Case 3). The conclusions are as follows. (1) Case 3 reduces lighting energy by 47.9–64.2% as compared to Case 1, and Case 3 reduces lighting energy compared to Case 2 when there are three occupants. (2) Case 3 improves indoor light environment comfort by increasing the uniformity by 17.8–49% compared to Case 2. These results confirm the effectiveness of Case 3 proposed in this study.

Keywords: general illumination; lighting control; location awareness technology; performance evaluation; energy saving

1. Introduction

Recently, the continual increase in energy consumption has been recognized as a serious problem, along with fossil fuel resource depletion and increasing carbon emissions. In response, research and technology development related to energy reduction are underway in various sectors, such as buildings, transport, and industry to solve this problem [1–3]. As energy consumption in the building sector accounts for as high as 1/2 and 1/3, respectively, of global electricity and all energy, research, and technological developments that are related to energy reduction in the building sector are increasing [4]. In particular, the lighting energy consumption of the building sector accounts for 25% of total energy consumption, according to the 2011 Buildings Energy Data Book from the DOE (Department of Energy) [5]. Therefore, various studies are being performed to reduce the lighting energy consumption in the building sector. These studies are focused on improving the efficiency of lighting equipment [6–9], improving the application of lighting equipment [10–13], and improving lighting control through environmental information collection sensors [14–16], which contribute to saving building energy. Recently, advanced technologies are coming to be integrated into the building sector with the introduction of net-zero energy homes, which refer to buildings with zero net energy consumption [17–20]. Moreover, technologies for lighting control and lighting energy reduction are becoming increasingly advanced with the introduction of location tracking technologies [21,22], connection with mobile devices [23,24], and Wireless Fidelity (Wi-Fi) technologies [25]. In particular, the occupant location-awareness technology in this study tracks and recognizes the location information of an occupant, which can be used to efficiently reduce lighting energy by preventing the use of unnecessary lighting when applied to the lighting control [21]. However, in previous related studies, the lighting control [22,25] implemented on-off and dimming controls only for lighting adjacent to the occupant's location. In these cases, the lights are Off for zones where occupants are not located. Such lighting control may cause indoor illuminance imbalance, which is inappropriate, as it provides an uncomfortable light environment to the occupant. In particular, this type of lighting control is expected to cause a more serious illuminance imbalance during nighttime, with no natural light entering from outside, as well as in cloudy weather conditions.

Therefore, the purpose of this study is to develop a dimming lighting control system and algorithm while using general illumination and location-awareness technology. The study also aims to test the effectiveness of this system in terms of lighting energy reduction and indoor light environment improvement by building a full-scale test bed.

1.1. Lighting Method and Lighting Control Method

Lighting methods for indoor spaces can be classified into the general lighting method and the local lighting method. The general lighting method can improve the indoor light environment by minimizing the indoor illuminance imbalance by controlling the entire indoor space with uniform brightness. On the other hand, the local lighting method can project a desired illuminance on the work surface, thereby improving the lighting efficiency as compared to the general lighting method. However, this method may reduce the light environment comfort by causing illuminance deviation in the indoor space [26]. In this regard, the dimming lighting control using general lighting and occupant location-awareness technology in this study monitors the occupant's location information and it applies general lighting in order to solve the illuminance imbalance that is caused by the local lighting method that controls only the lighting adjacent to the occupant, thereby saving lighting energy and improving the overall light environment.

The methods of controlling indoor artificial lighting can be divided into on-off lighting control, sensor-based lighting control, dimming lighting control, and mixed lighting control, as shown in Table 1 [22,27,28]. on-off lighting control is a low-cost and easy-to-install method that is operated with a simple switch, whereas sensor-based lighting control enables automatic control by detecting the occupant's movement as well as the indoor and outdoor illuminance. Dimming-based lighting control provides step-by-step illumination, which improves the visibility of the occupants and enables efficient energy saving. Dimming-based lighting control provides a phased illuminance, which improves the occupant's visual comfort and enables efficient energy saving. Finally, mixed lighting control is a method of enhancing lighting efficiency by mixing together the previous three methods. The lighting control method that is proposed in this study is a mixed lighting control method, as it is a combination of sensor-based lighting control and dimming-based lighting control. The reason for selecting this combination lighting control method as the method that this study intends to develop is based on occupant location-awareness and dimming control.

Table 1. Air cap specifications that are provided by the manufacturer.

Classification	Control Format	Characteristics
on-off Lighting control	Manual control	Lighting control with minimal cost, easy installation, and simple switch operation
Sensor Lighting control	Automation control	Lighting control based on movement of user and indoor/outdoor information
Dimming Lighting control	Manual/Automation control	Lighting control enabling illumination control for effective management of lighting energy and energy reduction
Mixed Lighting control	Manual/Automation control	Lighting control with mixed schemes of sensors, dimming, etc.

1.2. Technology Consideration for Implementing Location-Awareness Technology

Location recognition technology provides various occupant-oriented services by collecting and analyzing the location information of occupants and objects, and its range of application is expanding into various fields. The typical technologies that are used for implementing location-awareness include triangulation, scene analysis, and proximity [29]. The location-awareness method using triangulation basically calculates distance by using the geometrical characteristics of a triangle, which is based on the method of measuring distance from several reference points. The location-awareness method using scene analysis uses camera sensors, and it measures the location of the object to be analyzed by using the characteristics of the observed scene. The scene analysis method can be divided into the static and the differential analysis methods. The static analysis method compares the observed scene with the environmental characteristics of the location subject in order analyze, which needs to be stored in the database in advance, while the differential analysis method is based on the difference between continuous scenes. Scene analysis is advantageous in that the location measurement does not require geographical characteristics, such as distance or angle, and is possible through passive observation. However, as the system must be aware of the scene of the target location in advance in order to assess the location, the database must be rebuilt any time the analysis target is moved or the environment changes. The location-awareness method using proximity refers to a method of recognizing the location when the object to be located is near an object whose position is already known. This method can be divided into location-awareness by physical contact and that of inferring the location by an identification tag.

As shown in Table 2, there are three types of occupant location-awareness systems: macro location-awareness, micro location-awareness, and ad-hoc location-awareness, depending on the characteristics and awareness range of the occupant. When considering the size of the space and the indoor area, Zigbee, which is a type of micro location-awareness, is considered to be suitable for the occupant location-awareness system for indoor lighting control. Therefore, based on related studies [21], this study adopted and applied Zigbee, which is a micro location-awareness method, in order to implement the occupant location-awareness system and evaluate its performance.

Table 2. Classification and characteristics of location-awareness technology.

Classification of the Location-Awareness Technology		Position of Application	Range of Application	Characteristics
Macro method	GPS	Outdoor	Within 10 m	Suitable for outdoor environments
Micro method	Zigbee	Indoor	2–10 m	Receiver (tag) should be carried
				Low installation costs
				Significantly affected by environments
	Active Bat		Within 9 m	Requires a ceiling sensor grid
				Requires possession of Bat
	Active Badge		Within 5 m	Affected by the surrounding environment such as sunlight interference
	Radar		3–4 cm	Requires a wireless NIC
Ad-hoc method	Centroid	Outdoor, Indoor	-	-

1.3. Consideration of Previous Studies Related to Lighting Control

As shown in Table 3, research into developing efficient lighting control methods and technologies for saving building energy [22,25,30–35] has been continuously performed, and these studies induce efficient lighting energy reductions by considering indoor illuminance information as well as the presence of occupants. However, these studies have thus far focused on the development or method of a sensor network for indoor illuminance and occupancy sensing for lighting control; the actual lighting is controlled by the presence of the occupant or only the lighting adjacent to the occupant is controlled. Among these, studies that recognize the location of the occupant and control the lighting adjacent to the occupant [22,25,33,35] prove that this method is effective in reducing lighting energy by blocking unnecessary lighting control. However, these studies only examine controlling the lighting adjacent to the occupant, which might provide an unpleasant visual environment to the occupant by inducing an imbalance in indoor illuminance. This matter is also presented through the performance evaluation results in Section 3.1 of this study.

Table 3. Consideration of previous studies related to lighting control.

Author (Year of Publication)	Information Collected for Lighting Control	Lighting Control
CF Reinhart (2004) [30]	Illuminance, occupancy sensing (occupant's presence)	Lighting control according to occupant's presence
T. Leephakpreeda (2005) [31]	Illuminance, occupancy sensing (occupant's presence)	Lighting control according to occupant's presence
Nagy et al. (2015) [32]	Illuminance, occupancy motion sensing (occupant's presence)	Lighting control according to occupant recognition (motion)
Pandharipande and Caicedo (2015) [33]	Illuminance, occupancy sensing (occupant's location)	Occupant location recognition & lighting dimming control adjacent to occupant location
Choi et al. (2015) [22]	Illuminance, occupancy sensing (occupant's location)	Occupant location recognition & lighting dimming control adjacent to occupant location
Peruffo et al. (2015) [34]	Illuminance, occupancy sensing (occupant's presence)	Lighting dimming control according to occupant's presence
Caicedo et al. (2016) [35]	Illuminance, occupancy sensing (occupant's location)	Occupant location recognition & lighting dimming control adjacent to occupant location
Zou et al. (2018) [25]	Illuminance, occupancy sensing (occupant's location)	Occupant location recognition & lighting dimming control adjacent to occupant location

1.4. Consideration of Optimal Indoor Light Environment Standards

Maintaining a recommended level of indoor illumination is important not only in creating a comfortable light environment, but also in reducing building energy by blocking unnecessary lighting control [36,37]. In addition, this study needs to consider the recommended level of indoor illumination in order to calculate the lighting energy so as to maintain the optimal indoor illumination between performance evaluations. Therefore, this study considered the recommended levels of indoor illumination in the U.S. and Korea [38,39], as shown in Tables 4 and 5, respectively. Although the indoor illumination standards in the U.S. and Korea are similar in that the optimal illumination range is specified according to the type of activity and the lighting method used, the illumination standards of indoor space according to the classification differ in some ways. This study set 100 lx and 500 lx as the reference measures for the local lighting control for indoor general lighting and occupant location, respectively. These are based on the lower of the intersecting values for the illumination range of a workplace where visual work is not frequent and the general luminance against visual work is appropriate to the illumination standards of the U.S. and Korea. In addition, based on recommended levels of illumination of a workplace where visual work is not frequent, the illumination standards of the U.S. and Korea recommend maintaining 50 lx and 30 lx, respectively, in order to maintain a comfortable indoor light environment.

In addition to maintaining a recommended level of indoor illumination, an important factor for improving the indoor light environment is the uniformity of the indoor illumination. The uniformity is a value indicating the uniformity of the indoor illuminance, and the international standards recommend maintaining uniformity above 0.5 [40]. It is also recommended to maintain a minimum uniformity of 1/3 in spaces where lighting control is performed.

Table 4. Illuminating Engineering Society (IES) indoor illumination standards.

Type of Activity	Range of Illuminance (lx)			Reference Work Plane
	Minimum	Standard	Maximum	
Simple orientation for short/temporary visits	50	75	100	General lighting throughout spaces
Working spaces where visual tasks are only occasionally performed	100	150	200	
Performance of visual tasks of medium contrast	500	750	1000	Illuminance on task

Table 5. KS A 3011 Recommended levels of illumination.

Type of Activity	Illumination Range (lx)			Reference Work Surface Lighting Method
	Minimum	Standard	Maximum	
Workplace where visual work is not frequent	60	100	150	General lighting of space

2. Proposal and Performance Evaluation Environment Setting

2.1. The Concept of the Dimming Lighting Control Using General Lighting and Occupant Location-Awareness Technology

As shown in Figure 1, the dimming lighting control using general lighting and occupant location-awareness technology that is proposed in this study can be classified into occupant location recognition, indoor illumination information collection, and lighting control. The main contents are as follows.

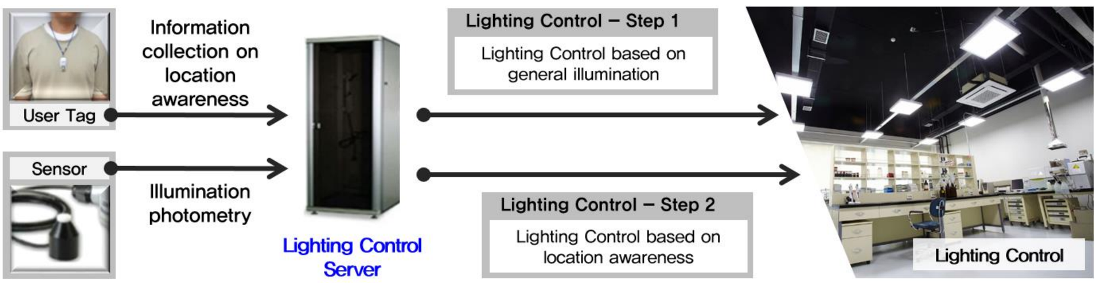

Figure 1. The concept of the lighting control system applying general illumination and location-awareness technology.

First, the lighting control server of the lighting control system that is proposed in this study tracks the occupant's location from the moment that he/she enters the room, and then monitors the occupant's location information in real-time. However, errors may occur in recognizing the occupant's location due to environmental factors, such as physical obstacles and the movement of the target. Therefore, this study divided the indoor space into a specific number of zones according to the size and characteristics of the space rather than collecting the exact coordinates of the occupant's location. This arrangement enables the recognition of the zone in which the occupant is located so as to confirm the occupant's location. Second, this study installed an illuminance sensor in each zone in order to collect indoor illumination information, and moved on to the lighting control phase by collecting the measured values of the illuminance sensor when the occupant would enter the room. The standards for the lighting control based on general lighting and occupant location-awareness in this study are 100 lx and 500 lx, respectively, as previously mentioned in Section 1.4. Third, the lighting control that is connected to the illuminance sensor in each zone is implemented in two steps according to the general lighting control and local lighting by recognizing the location of the occupant. The lighting control procedure is as follows: The first step of the lighting control that is performed when the occupant enters the room is the general lighting control, which maintains the measured indoor illumination value at 100 lx, regardless of the location information of the occupant. When the measured value of the illuminance sensor with the lowest illuminance value is below 100 lx, the general lighting control is designed to increase the dimming phase sequentially from the lighting that is connected to the illuminance sensor showing the minimum illuminance value. The general lighting control ends when the measured values of all of the illuminance sensors during this process are 100 lx or higher. We then proceed to the second step, which is the local lighting control according to occupant location recognition. However, the general lighting control of this study assumes that the illuminance decreases as the distance from the window increases. Thus, the lighting dimming control is performed sequentially from the zones that are distant from the window. The second step of the lighting dimming control according to occupant location recognition measures the illuminance of the zone where the occupant is located and it sequentially increases the dimming control phase so as to satisfy 500 lx when the illuminance is below 500 lx. This two-step lighting control method not only improves indoor illuminance imbalance, but it also allows for efficient energy reduction through location-based lighting control.

2.2. Algorithm Development for the Dimming Lighting Control Using General Lighting and Occupant Location-Awareness Technology

As shown in Figure 2, an algorithm was developed to implement the dimming lighting control using general lighting and occupant location-awareness technology proposed in this study. This algorithm is divided into three major stages: the general lighting control, occupant location recognition, and the local lighting control based on occupant location recognition for application. The details are as follows.

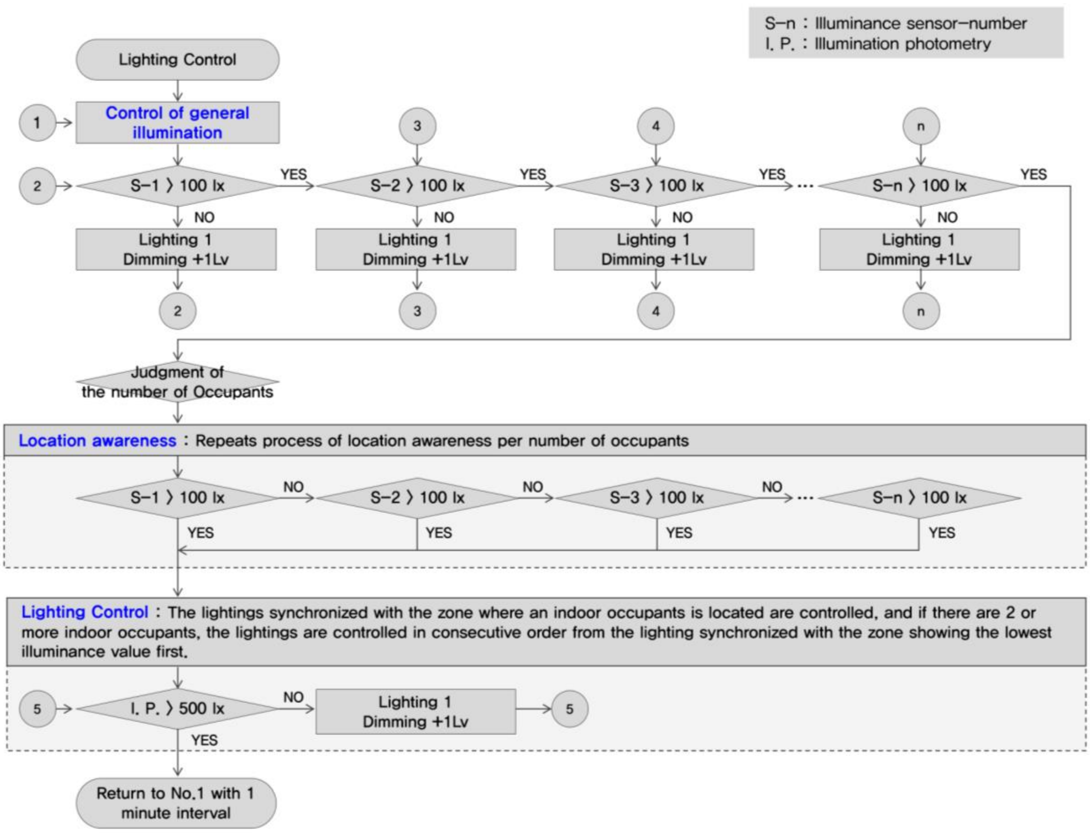

Figure 2. The algorithm for the dimming lighting control using the general lighting and occupant location-awareness technology.

First, the general lighting control is performed when the occupant first enters the room as the initial step of the lighting control. This general lighting control was designed to increase the dimming level of the lighting sequentially, so as to satisfy an illuminance of 100 lx or higher in all zones in the indoor space. However, since the lighting control of a particular zone can affect all of the spaces, the general lighting control performs the dimming lighting control sequentially from zones that are distant from the lighting window. This lighting control takes place prior to occupant location recognition, which minimizes the deterioration of indoor light environment comfort due to the lack of illuminance and any illuminance imbalance when the occupant enters the room. Second, the occupant location information recognition stage was designed to sequentially check the presence of an occupant, and when two or more occupants enter the room, the process of collecting occupant location information is repeated for each occupant. Third, the lighting that is associated with the zone where the occupant is located is controlled, and if the illuminance of the corresponding zone is below 500 lx, the dimming level of the lighting is sequentially increased to 500 lx. In addition, the system that is proposed in this study was designed to locate the occupant and control the lighting in one-minute intervals for performance evaluation. Therefore, adjustments will be necessary before this lighting control can be applied to an actual environment.

2.3. Performance Evaluation Environment Settings

This study established a full-scale test bed in order to evaluate the performance of the dimming lighting control while using general lighting and occupant location-awareness technology. The reason for adopting the performance evaluation method through a full-scale test bed is that it calculates the lighting energy consumption according to the implementation of the location-awareness system for lighting control and lighting equipment control. The size of the test bed built for performance evaluation was 4.9 m wide, 2.5 m high, and 6.6 m deep, as shown in Table 6 and Figure 3, and the size of the lighting window was 1.9 m wide and 1.7 m high. In addition, a blind (shading device) was installed on the lighting window in order to create an environment that is similar to actual conditions, and the angle of the slats of the blind was set to 90° for the performance evaluation. As the position of the lighting in the test bed was based on the IES four-point method [38], this study installed four LED-type lights, which offer an eight-step dimming control. The conical illuminance and light distribution of the lighting built for this study are shown in Figure 4. The illuminance distribution of the Zone set in this study will reach 500 lx through the eight-step dimming lighting control of the lighting connected to each Zone, even at night when no natural light enters the room. In addition, the occupant location-awareness system and the lighting control system of this study were implemented in cooperation with Samsung in Korea. The occupant location-awareness system built on the test bed consists of one master sensor and six detector sensors that collect Zigbee-type tags as well as occupant location information. In addition, the occupant location-awareness system in this study divides the location into four zones based on the occupant location information collected, and the division of the zones was determined after considering the error rate for occupant location awareness and the size of the space. In order to evaluate the performance according to the lighting control, this study linked Lighting 1, Lighting 2, Lighting 3, and Lighting 4 to Zone 1, Zone 2, Zone 3, and Zone 4, respectively, and the lighting of each zone was controlled according to the measurements of the illuminance sensors in that zone. The locations of the illuminance sensors were adjusted based on research showing that indoor average illuminance measurement is effective at a distance of 4.4 m from the lighting window [41], and four sensors were installed, as shown in Figure 5. In addition, the illuminance sensors were positioned 750 mm from the floor in consideration of the height of the working surface. This study established an energy monitoring system to monitor the energy consumption according to the lighting control, and the margin of error of the energy monitoring system is within 2%. This study installed an artificial solar irradiation system that can adjust the height, angle, and light quantity of the artificial light source outside the lighting window in order to create an outdoor light environment. Although the artificial solar irradiation system that was used in this study may differ from the Sun, the reasons for using this artificial solar irradiation system between performance evaluations are as follows: First, this study compares and analyzes the performance of lighting energy reduction for various lighting control methods, and accordingly, the same external environment should be created for the performance evaluation for each lighting control method; creating an artificial environment is an easy and effective way to maintain the same external environment between these performance evaluations. Second, the artificial solar irradiation system that is used in this study can obtain valid results between performance evaluations, as it received an A-grade for measurement uniformity according to ASTM E927-85. However, the artificial solar irradiation system was not capable of simulating the azimuth of the Sun. Therefore, the performance evaluation was only performed under a full south aspect.

Table 6. Overview of test bed, chamber.

Item	Specification
Room size and material	- Size: 4.9 m (W) × 6.6 m (D) × 2.5 m (H) - Room reflection factors: Ceiling 86%, Wall 46%, Floor 25%
Window size and material	- Size: 1.9 m (W) × 1.7 m (H) - Type: Double glazed 12 mm (3 CL + 6 A + 3 CL), Blind installation (slats angle −90°) - Transmissivity: 80%
Occupant location-awareness system	- Master sensor 1ea, detector sensor 6ea, Zigbee tag 3ea
Lighting	- Type: Eight-level dimming (LED type) 4ea, 600 × 600 mm - Dimming range: 10–100% - Energy consumption for phased light dimming: 12.3 kWh (Level 1), 18.3 kWh (Level 2), 22.0 kWh (Level 3), 27.7 kWh (Level 4), 34.0 kWh (Level 5), 38.5 kWh (Level 6), 42.6 kWh (Level 7), and 50.8 kWh (Level 8)
Illuminance sensor	- Sensing element: Silicon photo sensor, with filter - Detection range: 0–200,000 lx - Precision: ±3%
Artificial solar Light Radiation Apparatus	- Precision of solar light radiation: Grade A (according to ASTM E927-85) - Range of illumination: 0–80,000 lx - Directions: South aspect
Energy monitoring system	- Measurement capacity: Single phase (220 V, 1–50 A) - Error rate: Within 2.0% - Measurement items: Power/voltage/current, real-time, and accumulated amount

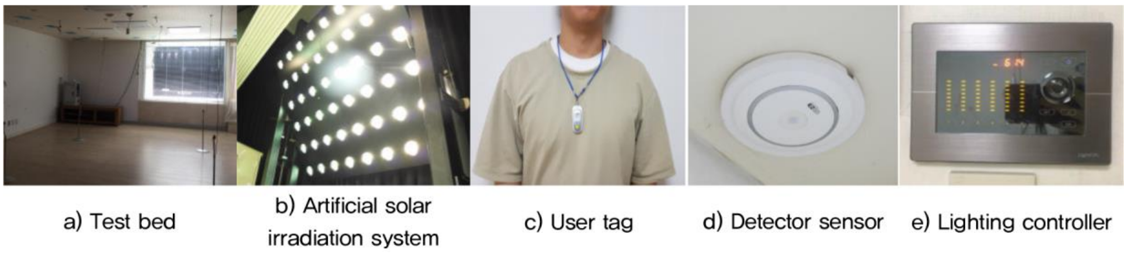

Figure 3. Overview of test bed and measurement apparatus.

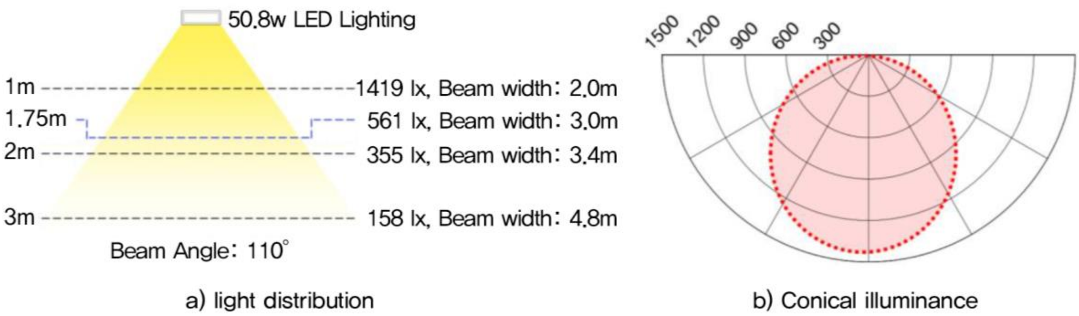

Figure 4. Light distribution and conical illuminance and of lighting.

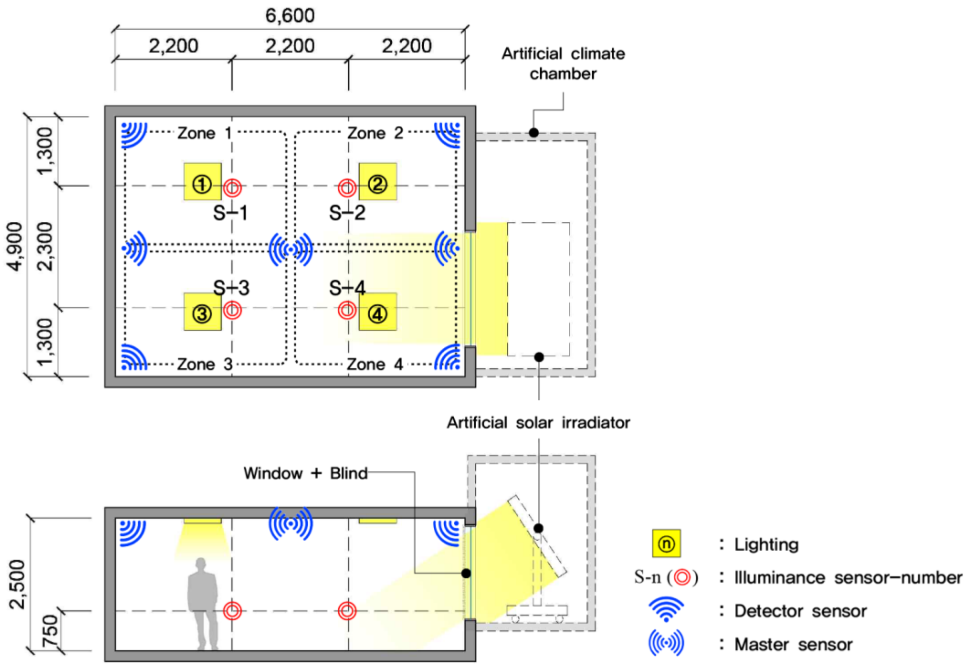

Figure 5. Test bed section, plane, and sensor location.

The performance evaluation was limited to summer, because the energy consumption of the building sector during summer is high. In addition, indoor lighting control is particularly important in summer, when the amount of natural light entering the room is low due to the high altitude [42]. Based on related studies [43,44], the external illuminance settings for each hour during summer were set from 10:00 to 15:00 in the daytime and from 20:00 to 23:00 at night, respectively, as shown in Table 7.

Table 7. The external illuminance and meridian altitude during summer by time period.

Item	Daytime			Nighttime
Time	10:00–12:00	12:00–13:00	13:00–15:00	20:00–23:00
External illuminance	70,000 lx	80,000 lx	70,000 lx	0 lx
Meridian altitude	76°			

2.4. Performance Evaluation Method

This study proposes a dimming lighting control system using general lighting and occupant location-awareness technology, and conducted a performance evaluation for lighting energy reduction and light environment improvement using a full-scale test bed. For this purpose, the performance evaluation method of this study was set as follows based on related studies [45,46].

First, this study compared and analyzed the performance of the dimming lighting control and the dimming lighting control using location-awareness technology in order to verify the effectiveness of the dimming lighting control using general lighting and occupant location-awareness technology. For this purpose, this study set the dimming lighting control, dimming lighting control while using location-awareness technology, and the dimming lighting control using general lighting and occupant location-awareness technology as Case 1, Case 2, and Case 3, respectively, as shown in Table 8. The application of location-awareness technology and general lighting yields the result of this study. Second, this study performed a performance evaluation for one to three occupants in order to evaluate the energy reduction performance of the lighting control according to occupant location recognition. The occupant's location was the same for each performance evaluation. However, this study assumed that the occupants moved every 30 min, and in the case of three occupants, only two persons were ever located in the same zone, considering the size of the zone. Third, this study calculated the amount of lighting energy consumption for each case, and the criteria for the lighting equipment control level and lighting energy consumption calculation derived from each case are as follows: The dimming lighting control (Case 1) in this study monitored the indoor illumination when the occupant entered the room and implemented the lighting control if the minimum value of the measured illumination is below 500 lx, regardless of the occupant location recognition. In addition, the dimming lighting control (Case 1) controlled all of the lights to the same level, and sequentially increased the lighting dimming level such that the indoor illuminance sensor value was above 500 lx. The lighting control ended when all of the measurements of indoor illumination reached 500 lx, and the lighting energy consumption of the dimming lighting control (Case 1) was derived by reflecting the level of control. The dimming lighting control using location-awareness technology (Case 2) was configured based on related research [22,25,33,35], and it worked by tracking the occupant's location upon entry to the room, then implementing the lighting control if the illumination in the zone where the occupant was located was below 500 lx. The dimming lighting control using location-awareness technology (Case 2) independently controlled the lighting connected to each zone, and only raised the lighting dimming level of the zone where the occupant was located until it reached 500 lx. The lighting control and power consumption at this time were calculated and reflected in the performance evaluation results of the dimming lighting control using location-awareness technology (Case 2). However, when two or more occupants were not in the same zone in Case 2, the lighting control was first applied in the zone with the lower illuminance value, and then subsequently applied in the other zones. For example, when occupants were located in Zone 1 and Zone 2, and the illuminances of Zone 1 and Zone 2 were 300 lx and 400 lx, respectively, the dimming lighting control using location-awareness technology (Case 2) implemented lighting control, as follows: First, among the zones where occupants were recognized, the dimming level of the light connected to Zone 1, where the illuminance value was low, was raised until it reached 500 lx. Next, the illuminance of Zone 2 was remeasured in order to check if it satisfied 500 lx, since the illuminance of Zone 1 can influence that of Zone 2 to satisfy 500 lx. If the illuminance of Zone 2 did not satisfy 500 lx after the lighting control was performed for Zone 1, the lighting dimming level of the light connected to Zone 2 was raised until it reached 500 lx. The lighting control ended when the illuminances of Zone 1 and Zone 2 both satisfied 500 lx, and the power consumption was calculated based on these results. The dimming lighting control using general lighting and occupant location-awareness technology (Case 3) was implemented using the control methods presented in Sections 2.1 and 2.2. Fourth, this study analyzed the uniformity of each case in order to derive the indoor light environment improvement rate according to the application of location-awareness technology, and the indoor uniformity of this study was calculated as the minimum illuminance for the average illumination.

Table 8. Case setting for performance evaluation.

Item	Dimming Lighting Control (Case 1)	Dimming Lighting Control Using Location-Awareness Technology (Case 2)	Dimming Lighting Control Using General Lighting and Location-Awareness Technology (Case 3)
Dimming control	Considered	Considered	Considered
Location-awareness technology	Not considered	Considered	Considered
General lighting control	Not considered	Not considered	Considered

3. Performance Evaluation Results and Discussion

3.1. Performance Evaluation Results

As shown in Tables 9–11, this study derived the lighting energy consumption and indoor uniformity for the dimming lighting control (Case 1), dimming lighting control using location-awareness technology (Case 2), and the dimming lighting control using general lighting and occupant location-awareness technology (Case 3). The details are as follows.

Table 9. Performance evaluation results based on one occupant.

Time	Location Awareness (Zone)	Dimming Lighting Control (Case 1)		Dimming Lighting Control Using Location-Awareness Technology (Case 2)			Dimming Lighting Control Using General Lighting and Location-Awareness Technology (Case 3)		
	1-2-3-4	L. C./I.	C.E	L. C./I.	C.E	U.R	L. C./I.	C.E	U.R
10:00	○-X-X-X	6+6+6+6/ 582-867-660-1046	77	8+Off+Off+Off/ 521-368-272-508	25	0.652	8+Off+Off+Off/ 521-368-272-508	25	0.652
10:30	X-○-X-X	6+6+6+6/ 582-867-660-1046	77	Off+4+Off+Off/ 43-561-101-557	14	0.137	1+3+Off+Off/ 121-500-130-545	17	0.375
11:00	X-○-X-X	6+6+6+6/ 594-909-670-1125	77	Off+3+Off+Off/ 47-537-109-623	11	0.144	1+3+Off+Off/ 133-542-140-624	17	0.371
11:30	X-X-○-X	6+6+6+6/ 594-909-670-1125	77	Off+Off+7+Off/ 150-353-547-584	21	0.367	1+Off+6+Off/ 213-356-519-577	25	0.513
12:00	○-X-X-X	6+6+6+6/ 594-909-670-1125	77	8+Off+Off+Off/ 533-409-282-587	25	0.623	8+Off+Off+Off/ 533-409-282-587	25	0.623
12:30	X-X-○-X	6+6+6+6/ 594-909-670-1125	77	Off+Off+7+Off/ 150-353-547-584	21	0.367	1+Off+6+Off/ 213-356-519-577	25	0.513
13:00	X-X-X-○	6+6+6+6/ 594-909-670-1125	77	Off+Off+Off+Off/ 32-330-101-554	0	0.127	1+Off+Off+Off/ 118-335-132-555	6	0.415
13:30	○-X-X-X	6+6+6+6/ 594-909-670-1125	77	8+Off+Off+Off/ 533-409-282-587	25	0.623	8+Off+Off+Off/ 533-409-282-587	25	0.623
14:00	X-○-X-X	6+6+6+6/ 594-909-670-1125	77	Off+3+Off+Off/ 47-537-109-623	11	0.144	1+3+Off+Off/ 133-542-140-624	17	0.371
14:30	X-X-○-X	6+6+6+6/ 582-867-660-1046	77	Off+Off+6+Off/ 138-311-537-506	21	0.370	1+Off+6+Off/ 201-314-509-498	21	0.530
15:00	X-X-X-○	6+6+6+6/ 582-867-660-1046	77	Off+Off+Off+1/ 23-319-95-598	6	0.089	1+Off+Off+1/ 109-324-126-599	12	0.377
20:00	○-X-X-X	6+6+6+6/ 561-578-569-570	77	8+Off+Off+Off/ 521-78-181-29	25	0.147	8+1+Off+1/ 527-176-188-178	38	0.660
20:30	X-○-X-X	6+6+6+6/ 561-578-569-570	77	Off+8+Off+Off/ 71-540-27-135	25	0.144	2+8+1+Off/ 251-547-164-141	41	0.514
21:00	X-X-○-X	6+6+6+6/ 561-578-569-570	77	Off+Off+8+Off/ 135-27-511-38	25	0.154	2+2+7+1/ 273-201-574-206	46	0.641
21:30	X-X-X-○	6+6+6+6/ 561-578-569-570	77	Off+Off+Off+8/ 24-154-46-517	25	0.129	2+2+2+7/ 214-298-185-565	49	0.586
22:00	○-X-X-X	6+6+6+6/ 561-578-569-570	77	8+Off+Off+Off/ 521-78-181-29	25	0.147	8+1+Off+1/ 527-176-188-178	38	0.660
22:30	X-○-X-X	6+6+6+6/ 561-578-569-570	77	Off+8+Off+Off/ 71-540-27-135	25	0.144	2+7+2+Off/ 170-537-197-149	41	0.567
		Total consumption of electric power = 1.309 kWh Average uniformity ratio of illumination = 0.818		Total consumption of electric power = 0.330 kWh Average uniformity ratio of illumination = 0.265			Total consumption of electric power = 0.468 kWh Average uniformity ratio of illumination = 0.531		

Legend: L. C. = Light Control (Lighting 1 Dimming level + Lighting 2 Dimming level + Lighting 3 Dimming level + Lighting 4 Dimming level). I. = Illumination (Illumination sensor 1 value-Illumination sensor 2 value-Illumination sensor 3 value-Illumination sensor 4 value). C.E = Consumption of electric power. U.R = Uniformity ratio of illumination.

Table 10. Performance evaluation results based on two occupants.

Time	Location Awareness (Zone)	Dimming Lighting Control (Case 1)		Dimming Lighting Control Using Location-Awareness Technology (Case 2)			Dimming Lighting Control Using General Lighting and Location-Awareness Technology (Case 3)		
	1-2-3-4	L. C./I.	C.E	L. C./I.	C.E	U.R	L. C./I.	C.E	U.R
10:00	◎-X-X-X	6+6+6+6/ 582-867-660-1046	77	8+Off+Off+Off/ 521-368-272-508	25	0.652	8+Off+Off+Off/ 521-368-272-508	25	0.652
10:30	X-○-X-○	6+6+6+6/ 582-867-660-1046	77	Off+4+Off+Off/ 43-561-101-557	14	0.137	1+3+Off+Off/ 121-500-130-545	17	0.375
11:00	X-○-○-X	6+6+6+6/ 594-909-670-1125	77	Off+3+7+Off/ 165-559-555-653	32	0.342	1+3+7+Off/ 229-562-527-645	32	0.466
11:30	X-X-◎-X	6+6+6+6/ 594-909-670-1125	77	Off+Off+7+Off/ 150-353-547-584	21	0.367	1+Off+6+Off/ 213-356-519-577	25	0.513
12:00	○-X-X-○	6+6+6+6/ 594-909-670-1125	77	8+Off+Off+Off/ 533-409-282-587	25	0.623	8+Off+Off+Off/ 533-409-282-587	25	0.623
12:30	X-X-○-○	6+6+6+6/ 594-909-670-1125	77	Off+Off+7+Off/ 150-353-547-584	21	0.367	1+Off+6+Off/ 213-356-519-577	25	0.513
13:00	X-X-X-◎	6+6+6+6/ 594-909-670-1125	77	Off+Off+Off+Off/ 32-330-101-554	0	0.127	1+Off+Off+Off/ 118-335-132-555	6	0.415
13:30	○-○-X-X	6+6+6+6/ 594-909-670-1125	77	8+2+Off+Off/ 541-541-287-629	35	0.575	8+2+Off+Off/ 541-541-287-629	35	0.575
14:00	X-◎-X-X	6+6+6+6/ 594-909-670-1125	77	Off+3+Off+Off/ 47-537-109-623	11	0.144	1+3+Off+Off/ 133-542-140-624	17	0.371
14:30	X-X-○-○	6+6+6+6/ 582-867-660-1046	77	Off+Off+7+Off/ 138-311-537-506	21	0.370	1+Off+6+Off/ 201-314-509-498	25	0.530
15:00	○-X-X-○	6+6+6+6/ 582-867-660-1046	77	8+Off+Off+Off/ 521-368-272-508	25	0.652	8+Off+Off+Off/ 521-368-272-508	25	0.652
20:00	○-○-X-X	6+6+6+6/ 561-578-569-570	77	8+7+Off+Off/ 555-522-205-156	47	0.433	8+4+1+Off/ 554-507-235-209	45	0.555
20:30	X-◎-X-X	6+6+6+6/ 561-578-569-570	77	Off+8+Off+Off/ 71-540-30-135	25	0.158	2+8+1+Off/ 251-547-164-141	41	0.514
21:00	X-X-○-○	6+6+6+6/ 561-578-569-570	77	Off+Off+8+7/ 156-168-542-502	47	0.457	2+2+7+7/ 292-294-535-539	61	0.704
21:30	X-○-X-○	6+6+6+6/ 561-578-569-570	77	Off+8+Off+5/ 81-655-48-508	42	0.151	2+8+1+5/ 262-662-195-514	58	0.479
22:00	◎-X-X-X	6+6+6+6/ 561-578-569-570	77	8+Off+Off+Off/ 521-78-181-32	25	0.162	8+1+Off+1/ 527-176-188-178	38	0.660
22:30	X-○-○-X	6+6+6+6/ 561-578-569-570	77	Off+8+8+Off/ 206-570-542-174	51	0.466	2+7+8+Off/ 334-565-530-179	56	0.445
		Total consumption of electric power = 1.309 kWh Average uniformity ratio of illumination = 0.818		Total consumption of electric power = 0.467 kWh Average uniformity ratio of illumination = 0.364			Total consumption of electric power = 0.556 kWh Average uniformity ratio of illumination = 0.532		

Legend: ◎ = two occupants located in the same zone. L. C. = Light Control (Lighting 1 Dimming level + Lighting 2 Dimming level + Lighting 3 Dimming level + Lighting 4 Dimming level). I. = Illumination (Illumination sensor 1 value-Illumination sensor 2 value-Illumination sensor 3 value-Illumination sensor 4 value). U.R = Uniformity ratio of illumination. C.E = Consumption of electric power.

Table 11. Performance evaluation results based on three occupants.

Time	Location Awareness (Zone)	Dimming Lighting Control (Case 1)		Dimming Lighting Control Using Location-Awareness Technology (Case 2)			Dimming Lighting Control Using General Lighting and Location-Awareness Technology (Case 3)		
	1-2-3-4	L. C./I.	C.E	L. C./I.	C.E	U.R	L. C./I.	C.E	U.R
10:00	◎-X-X-○	6+6+6+6/ 582-867-660-1046	77	8+Off+Off+Off/ 521-368-272-508	25	0.652	8+Off+Off+Off/ 521-368-272-508	25	0.652
10:30	X-○-○-○	6+6+6+6/ 582-867-660-1046	77	Off+3+7+Off/ 153-517-545-575	32	0.342	1+2+4+Off/ 217-501-503-576	29	0.483
11:00	X-○-◎-X	6+6+6+6/ 594-909-670-1125	77	Off+3+7+Off/ 165-559-555-653	32	0.342	1+3+7+Off/ 229-562-527-645	32	0.466
11:30	X-X-◎-○	6+6+6+6/ 594-909-670-1125	77	Off+Off+7+Off/ 150-353-547-584	21	0.367	1+1+6+Off/ 213-356-519-577	25	0.513
12:00	○-○-X-○	6+6+6+6/ 594-909-670-1125	77	8+2+Off+Off/ 541-541-287-629	35	0.575	6+2+1+Off/ 503-521-287-679	34	0.578
12:30	○-X-◎-X	6+6+6+6/ 594-909-670-1125	77	8+Off+4+Off/ 612-422-557-596	39	0.772	8+Off+4+Off/ 612-422-557-596	39	0.772
13:00	X-○-○-○	6+6+6+6/ 594-909-670-1125	77	Off+3+7+Off/ 165-567-621-661	32	0.328	1+2+5+Off/ 209-502-564-605	32	0.444
13:30	○-○-○-X	6+6+6+6/ 594-909-670-1125	77	8+2+4+Off/ 620-553-562-638	48	0.932	8+2+4+Off/ 620-553-562-638	48	0.932
14:00	X-◎-X-○	6+6+6+6/ 594-909-670-1125	77	Off+3+Off+Off/ 47-537-109-623	11	0.144	1+3+Off+Off/ 133-542-140-624	17	0.371
14:30	X-X-○-◎	6+6+6+6/ 582-867-660-1046	77	Off+Off+7+Off/ 138-311-537-506	21	0.370	1+Off+6+Off/ 201-314-509-498	25	0.530
15:00	○-X-○-○	6+6+6+6/ 582-867-660-1046	77	8+Off+4+Off/ 600-380-547-518	39	0.744	8+Off+4+Off/ 600-380-547-518	39	0.744
20:00	○-○-○-X	6+6+6+6/ 561-578-569-570	77	8+7+6+Off/ 651-542-592-177	64	0.361	8+7+6+Off/ 651-542-592-177	64	0.361
20:30	○-◎-X-X	6+6+6+6/ 561-578-569-570	77	8+7+Off+Off/ 555-522-205-156	47	0.433	8+4+1+Off/ 554-507-235-196	45	0.525
21:00	○-X-○-○	6+6+6+6/ 561-578-569-570	77	8+Off+6+7/ 618-237-599-518	66	0.481	8+1+6+5/ 600-166-572-501	68	0.362
21:30	X-○-○-○	6+6+6+6/ 561-578-569-570	77	Off+8+8+4/ 212-662-556-500	65	0.441	2+6+5+2/ 384-551-530-510	55	0.777
22:00	◎-○-X-X	6+6+6+6/ 561-578-569-570	77	8+7+Off+Off/ 555-522-205-156	47	0.433	8+4+1+Off/ 554-507-235-196	45	0.525
22:30	○-○-X-○	6+6+6+6/ 561-578-569-570	77	8+7+Off+5/ 572-734-230-541	64	0.480	8+5+1+3/ 602-640-344-513	60	0.656
		Total consumption of electric power = 1.309 kWh Average uniformity ratio of illumination = 0.818		Total consumption of electric power = 0.688 kWh Average uniformity ratio of illumination = 0.480			Total consumption of electric power = 0.682 kWh Average uniformity ratio of illumination = 0.570		

Legend: ◎ = two occupants located in the same zone. L. C. = Light Control (Lighting 1 Dimming level + Lighting 2 Dimming level + Lighting 3 Dimming level + Lighting 4 Dimming level). I. = Illumination (Illumination sensor 1 value-Illumination sensor 2 value-Illumination sensor 3 value-Illumination sensor 4 value). U.R = Uniformity ratio of illumination. C.E = Consumption of electric power.

First, the dimming lighting control (Case 1) showed the same lighting energy consumption of 1.309 kWh regardless of the number of occupants, as no occupant location recognition was applied. In addition, the lighting control level was maintained at the same dimming level of 6 during both day and night.

Second, the dimming lighting control using location-awareness technology (Case 2) reflects the occupant's location information. Accordingly, the lighting energy consumption levels for one occupant, two occupants, and three occupants varied significantly at 0.334 kWh, 0.467 kWh, and 0.688 kWh, respectively. In addition, the lighting control and lighting equipment energy consumption varied depending on the occupant's location during the day and night.

Third, the lighting energy consumption of the dimming lighting control using general lighting and occupant location-awareness technology (Case 3) was 0.468 kWh, 0.556 kWh, and 0.682 kWh, respectively, for one occupant, two occupants, and three occupants. The lighting energy consumption of the dimming lighting control using general lighting and occupant location-awareness technology (Case 3) was lower than the dimming lighting control (Case 1), but higher than the dimming lighting control using location-awareness technology (Case 2). However, in the case of three occupants, the lighting energy consumption of the dimming lighting control using general lighting and occupant location-awareness technology (Case 3) was 0.006 kWh less than that of the dimming lighting control using location-awareness technology (Case 2).

Fourth, this study identified the uniformity through the distribution of indoor illumination according to each lighting control, and the average indoor uniformity of the dimming lighting control (Case 1) was 0.818. In addition, as shown in Tables 9–11, the average indoor uniformities of the dimming lighting control using location-awareness technology (Case 2) for one occupant, two occupants, and three occupants were 0.271, 0.358, and 0.480, respectively. These results demonstrate that an uncomfortable light environment might be created when lighting control is performed only for the lighting adjacent to the occupant, as previously mentioned in Section 1.3. In addition, in the case of one occupant during the nighttime, the minimum indoor illumination was below 30 lx for the dimming lighting control using location-awareness technology (Case 2), which is below the recommended level of illumination for a "workplace for simple work for a short time" of 30 lx considered in Section 1.4; this results in a uncomfortable visual environment. In contrast, the dimming lighting control using general lighting and occupant location-awareness technology (Case 3) showed indoor uniformities of 0.531, 0.528, and 0.584, respectively, for one occupant, two occupants, and three occupants.

3.2. Discussion on the Performance Evaluation Results

This study developed a dimming lighting control system using general lighting and occupant location-awareness technology (Case 3). The objective was to solve the problems of illuminance imbalance and indoor light environment deterioration that are caused by conventional lighting control methods based on occupant location recognition, which control only the lighting adjacent to the occupant. The dimming lighting control system using general lighting and occupant location-awareness technology (Case 3) first implements general lighting when the occupant enters the room so that the illumination of the indoor space satisfies the minimum recommended illumination of 100 lx for "working spaces where visual tasks are only occasionally performed". Subsequently, an illumination of 500 lx is provided for visual work by controlling the lighting adjacent to the occupant. This not only reduces the lighting energy efficiency but it also addresses the illuminance imbalance problem. This study conducted a performance evaluation for verification, and the results derived earlier are discussed below.

First, the dimming lighting control (Case 1) shows the same level of lighting control both day and night during summer because of the low amount of light entering the room due to the high solar altitude. This is also why the dimming lighting control (Case 1) in this study controls the lighting at the same level, so as to ensure that the measurements of all illuminance sensors satisfy 500 lx.

Second, the dimming lighting control using location-awareness technology (Case 2) tracks the occupant's location and only controls the lighting in the zone where the occupant is located. Therefore, as shown in Figure 6, Case 2 can efficiently reduce lighting energy by 47.4–74.8% as compared to the dimming lighting control (Case 1). In particular, the dimming lighting control using location-awareness technology (Case 2) does not implement any lighting control in Zone 4, where the illuminance is always high during the daytime, as it is near the lighting window. This explains the increased efficiency of lighting energy reduction.

Third, the dimming lighting control using general lighting and occupant location-awareness technology (Case 3) developed through this study can reduce lighting energy by 47.9–64.2% as compared to the dimming lighting control (Case 1). The dimming lighting control using general lighting and occupant location-awareness technology (Case 3) implements not only the lighting control according to the occupant's location, but also implements the lighting control in advance. As a result, the illuminance of the overall indoor space satisfies 100 lx, and the lighting energy consumption is increased as compared to the dimming lighting control using location-awareness technology (Case 2). However, as shown in Figure 6, the rate of increase of lighting energy consumption of the dimming lighting control using general lighting and occupant location-awareness technology (Case 3) is lower compared to the dimming lighting control using location-awareness technology (Case 2) as the number of occupants increases. In particular, in the case of 3 occupants, the lighting energy consumption of the dimming lighting control using general lighting and occupant location-awareness technology (Case 3) is lower than that of the dimming lighting control while using location-awareness technology (Case 2). Although the dimming lighting control using general lighting and occupant location-awareness technology (Case 3) uses a relatively larger number of lightings as compared to the dimming lighting control using location-awareness technology (Case 2), the dimming level of each lighting is controlled at a low level. In contrast, the dimming lighting control using location-awareness technology (Case 2) controls a smaller number of lightings compared to the dimming lighting control using general lighting and occupant location-awareness technology (Case 3), but each lighting requires a relatively higher dimming level. This demonstrates the effectiveness of the dimming lighting control using general lighting and occupant location-awareness technology (Case 3) that was developed through this study. Furthermore, the developed technology will remain effective when applied to spaces with a large number of occupants.

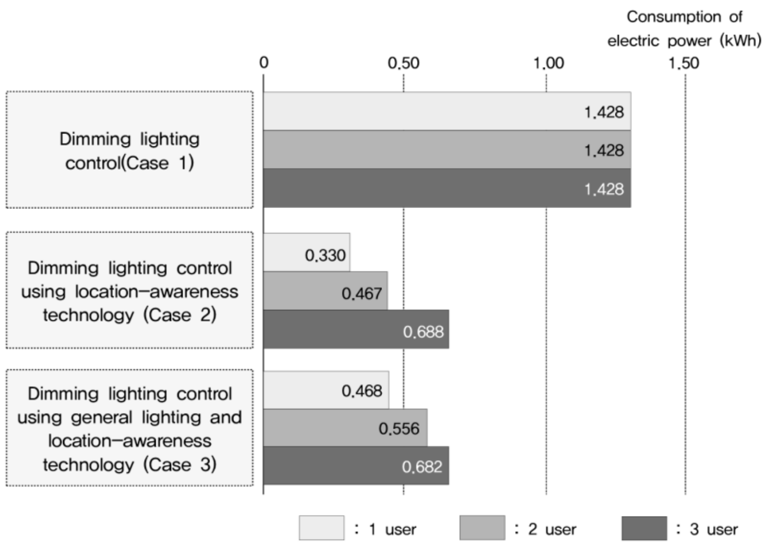

Figure 6. Consumption of electric power according to the lighting control method.

Fourth, as shown in Figure 7, the lighting control according to occupant location recognition reduced the uniformity, as compared to the dimming lighting control (Case 1) in which the lightings are collectively controlled to the same level. Accordingly, the average uniformity of the dimming lighting control using location-awareness technology (Case 2) does not satisfy the recommended level of indoor uniformity (0.5), referred to in Section 1.4. As the uniformity level is irrespective of the number of occupants, it is therefore analyzed to be an uncomfortable light environment. Particularly in the case of one occupant, the average indoor uniformity of the dimming lighting control using location-awareness technology (Case 2) is below 0.3, which is deemed to be an unsuitable indoor light environment. However, the dimming lighting control using general lighting and occupant location-awareness technology (Case 3) proposed in this study first implements general lighting in order to partially improve the illuminance imbalance problem, and it satisfies the uniformity of 0.5 or higher, regardless of the number of occupants. In addition, the dimming lighting control using general lighting and occupant location-awareness technology (Case 3) improves the indoor uniformity by 17.8–49.0% depending on the number of occupants compared to the dimming lighting control using location-awareness technology (Case 2). This indicates that the use of a lighting control system that employs occupant location recognition improves the illuminance imbalance problem.

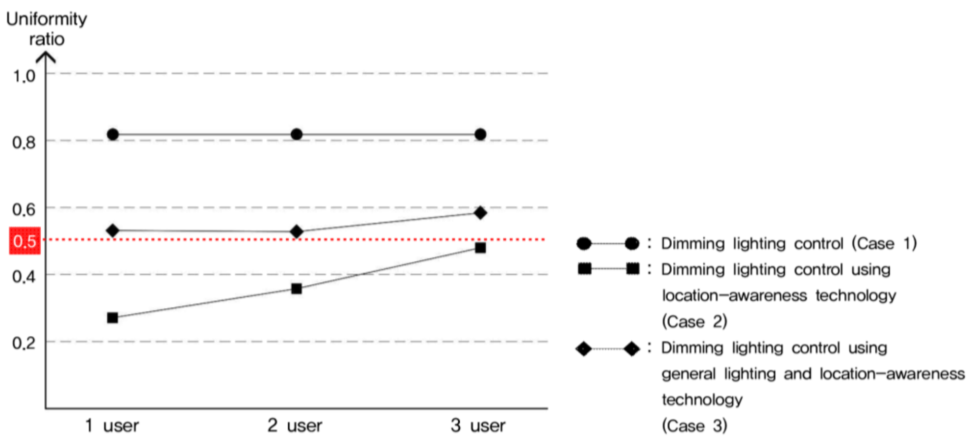

Figure 7. Average uniformity ratio according to the lighting control method.

Fifth, in summary of the contents above, the dimming lighting control using general lighting and occupant location-awareness technology (Case 3) proposed in this study is shown to be a significant lighting control method that can reduce lighting energy and improve indoor uniformity.

4. Conclusions

This study developed a dimming lighting control system using general lighting and occupant location-awareness technology (Case 3). The objective was to improve the illuminance imbalance problem caused by lighting control focused only on the occupant's location. This study verified the effectiveness of the proposed method by conducting a performance evaluation on lighting energy reduction and uniformity improvement using a full-scale test bed. The conclusion is as follows.

First, the dimming lighting control using general lighting and occupant location-awareness technology (Case 3) developed through this study is a system that is capable of reducing lighting energy and improving indoor uniformity by ensuring the overall illumination of the indoor space through the general lighting control of the indoor space and the local lighting control of the zone where the occupant is located, according to occupant location recognition.

Second, the dimming lighting control using general lighting and occupant location-awareness technology (Case 3) can reduce lighting energy by 47.9–64.2% as compared to the dimming lighting control (Case 1), thus enabling efficient lighting energy reduction.

Third, the dimming lighting control using general lighting and occupant location-awareness technology (Case 3) shows a higher lighting energy consumption when compared to the dimming lighting control using location-awareness technology (Case 2), which simply performs lighting control in the zone where the occupant is located. However, the rate of increase of lighting energy consumption, according to an increase of occupants in the dimming lighting control using general lighting and occupant location-awareness technology (Case 3), is lower than that in the dimming lighting control using location-awareness technology (Case 2). Therefore, this lighting control technology is considered to be suitable for spaces with a large number of occupants.

Fourth, the dimming lighting control using general lighting and occupant location-awareness technology (Case 3) improves the indoor uniformity by 17.8–49.0% as compared to the dimming lighting control using location-awareness technology (Case 2), indicating that it is suitable for improving indoor lighting comfort.

This study proposed a dimming lighting control using general lighting and occupant location-awareness technology (Case 3) in order to address the problems of conventional lighting control methods that are based on occupant location recognition, and demonstrated that the developed system reduces lighting energy and improves indoor comfort while using a full-scale test bed. In addition, the effectiveness of the developed technology was verified by performing diverse performance evaluations according to occupant location recognition and the number of occupants. However, the main limitation of this study is that the performance evaluation was conducted under an artificial environment using an artificial solar irradiation system and only during summer time. Therefore, in order to improve the results, follow-up studies that consider a number of variables, such as seasonal solar altitude and demand illuminance depending on the characteristics of the building, along with performance evaluations in real-world environments, will be necessary in the future. Moreover, future studies should be guaranteed with an emphasis on development of various lighting control technologies and also extended evaluation employing actual environmental factors, such as moving line of an indoor occupant and different arrangement of the furniture.

Author Contributions: H.L. developed the main idea of the current study. H.L. and C.-h.C. performed and interpret the analysis, and wrote the manuscript. M.S. reviewed the paper. All authors have read and approved the final manuscript.

Funding: This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) [grant numbers NRF-2018R1C1B4A01018660]. This work was supported by the Technology development Program(S2404849) funded by the Ministry of SMEs and Startups (MSS, Korea).

Conflicts of Interest: The authors declare no conflict of interest.

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