

Article

Digital Twin-Based Assessment Framework for Energy Savings in University Classroom Lighting

Hyuncheol Seo  and Woo-Seung Yun * 

School of Architectural, Civil, Environmental and Energy Engineering, Kyungpook National University, Daegu KS002, Korea; charles@knu.ac.kr

* Correspondence: bmqwe011@knu.ac.kr; Tel.: +82-53-950-5597

Abstract: In this paper, a digital twin-based assessment framework is proposed to determine which energy-saving technologies and strategies will work best in existing buildings. The proposed framework is based on a digital twin that integrates the existing building's hardware system, the building's operational schedule database, and a probabilistic model of occupant behavior. A digital model was constructed based on field measurements and database integration for a case study involving nine university buildings and 55 classrooms. As a result, in the classrooms involved in the case study, the lighting was turned on in the absence of occupants for an average of 10.7 h a day. The results indicate that it is very important to turn off the lights after the last hour of use in university classrooms in South Korea and that it is possible to reduce power consumption by more than 60% by employing an off strategy involving a passive infrared sensor or manager. Additionally, LED lighting in most classrooms is over-designed, which indicates that 46% of the energy consumed can be saved by adjusting the luminance level to an appropriate range.

Keywords: digital twin; lighting system; energy savings; university classroom



Citation: Seo, H.; Yun, W.-S. Digital Twin-Based Assessment Framework for Energy Savings in University Classroom Lighting. *Buildings* **2022**, *12*, 544. <https://doi.org/10.3390/buildings12050544>

Academic Editors: David J. Edwards, Clinton Aigbavboa, Obuks Ejohwomu and Chris Roberts

Received: 25 March 2022

Accepted: 24 April 2022

Published: 25 April 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The building sector consumes about 20–40% of global energy [1–3], and CO₂ emissions from building operations account for approximately 10% of global greenhouse gas emissions [3]. Lighting accounts for about 18–60% of the total energy used in building operations [4–9]. In particular, lighting accounts for about 23–42% of total energy used in educational buildings [10–12].

As lighting energy has an important meaning in educational buildings, various strategies for reducing lighting energy have been employed. Retrofitting light sources, one of the representative strategies for reducing energy used for lighting in buildings, has been reported to have an energy saving potential of 11–62% [12–22]. Another notable strategy involves reducing illuminance levels to appropriate ranges. This strategy has energy saving potential because the lighting systems of many buildings are over-designed [23]. Yet another representative strategy for saving energy in lighting focuses on the use of a control system. It has been reported that energy savings of 20–93% can be derived from introducing an occupancy control system and PIR (passive infrared) lighting [13]. When occupancy follows a regular schedule, time scheduling-based controls [19] can save energy by turning the lights on/off at preset times. A daylight-linked control system [24] dims or turns lights on/off based on the amount of illuminance coming in through a room's windows. These control systems can be implemented not only through hardware composed of sensors and actuators but also through planned manual management.

Strategies for saving lighting energy in buildings should be deployed based on quantitative analyses. Several studies [25,26] present the optimization and design method involving competing criteria such as energy efficiency with occupant comfort. However, a strategy's effect varies with building characteristics (e.g., usage schedule and occupancy

characteristics). Therefore, a comprehensive analysis of the various factors should be performed to quantify its effect. For example, when considering a university classroom, the design plan of the building, the information of the installed system, the lecture schedule, the occupancy probabilities, and the occupants' levels of awareness concerning the lighting system operation should be considered. It should also be taken into account, especially in public spaces such as university buildings, that the lecture schedule, the occupancy probabilities, and the occupants' levels of awareness may vary over time.

A digital twin is a virtual representation of the counterpart of a real-world building environment. The integration of the sensor system and the database, which is currently under rapid development, is accelerating the implementation of a digital twin. The decision support system integrating digital twins is expected to assist the designer and operator in defining the optimal design/control strategy [27,28].

In this study, we demonstrated a digital twin-based assessment framework for assessing energy saving strategies for the lighting in university buildings. In this proposed framework, the design plan of the building, the stochastic lighting operating schedule based on occupant behavior, and the building usage schedule are integrated into a digital twin model. Based on this model, the effect of each energy-saving strategy is quantified and analyzed. The evaluation process includes an analysis of existing saving strategies as well as a quantification of the effect of each measure to be implemented.

The structure of this paper is as follows. In Section 2, various studies on saving lighting energy are reviewed. Section 3 provides the details of the framework proposed in this paper. In Section 4, a case study based on field surveys and data from university buildings in South Korea is presented to illustrate how the proposed framework could be applied. Energy saving scenarios are configured based on representative measures of the strategies reviewed in Section 2, and the energy saving potential of each scenario is evaluated using the proposed framework. Finally, in Section 5, conclusions are discussed.

2. Energy Saving Strategies for Building Lighting

Various studies have been conducted to reduce energy consumption for lighting in buildings. The developed methods can be largely divided into retrofitting and control systems.

2.1. Retrofitting

The retrofitting method refers to the process of replacing the lighting equipment itself and can be categorized as: (1) replacing the type of luminaire, or (2) reducing the lighting output to provide an appropriate level of illuminance.

The replacement method is the most common retrofitting strategy and has great energy saving potential [13]. Various studies on the energy savings achieved through the replacement of lighting fixtures have been conducted. Mahlia et al. [14] analyzed the energy savings due to a lighting retrofit in the residential sector in Malaysia. The energy savings were analyzed assuming that 25%, 50%, and 75% of the inefficient lights were replaced, and it was concluded that a significant amount of energy could be saved. In another paper, Mahila et al. [12] analyzed the energy saving potential of a lighting retrofit in campus buildings at the University of Malaya. Approximately 90% of the lighting at the site was fluorescent, and when these fixtures were replaced with more efficient lamps, energy consumption declined approximately 40%. Clarke-Sather et al. [15] analyzed the effect of a lighting retrofit in China's rural Gansu Province. It was concluded that about a 27% energy saving could be achieved by replacing incandescent light bulbs with compact fluorescent light bulbs in the target area. Bonomolo et al. [16] applied lighting retrofitting to an educational building in Italy and analyzed various types of lighting retrofit cases according to the amount of solar radiation. Berardi et al. [17] analyzed various energy retrofitting strategies at a school located in the Barcelona metropolitan area and concluded that replacing fluorescent lamps with LEDs would reduce the energy demand by 11%. Josijević et al. [18] suggested a methodology for evaluating the energy saving potential in retrofitting the lighting for nine high schools located in Kragujevac, Serbia. It produced

an energy saving of 53–62%. In [19], the potentials of various energy efficiency measures, including lighting, were quantified for school buildings in hot climates. The analysis indicated that lighting replacement measures could reduce the buildings' fossil energy consumption in the operations and maintenance phase by 9.54–12.05%. In addition, the energy saving achieved by replacing non-LED lights with effective LED lights has been analyzed in the United States [20], Turkey [21], and South Africa [22].

In addition to changing the type of lighting, an appropriate reduction in illuminance level can be an effective way to save energy. EN 12464-1 [29] recommends an illuminance of 500 lux for a classroom used for evening classes and adult education. Therefore, it is possible to reduce energy consumption by reducing any illuminance level exceeding the recommended level. Baker [23] analyzed trends in retrofitting projects in Texas, USA based on four years of energy efficiency incentive programs. According to the results, the number of lights decreased in most cases, partly because most existing lighting systems are over-designed.

2.2. Control Systems

The control system method reduces energy consumption by turning lights on/off appropriately and dimming them. These systems can be divided into occupancy control systems, time scheduling-based control systems, and daylight-linked control systems.

The occupancy control systems detect occupants with sensors and adjust the lighting accordingly. According to a review of previous studies conducted in [13], occupancy control systems have expected energy savings of about 20–93%. Thus, this method is often used in buildings. Richman et al. [30] analyzed the energy savings achieved while adjusting various parameters related to the operation of an occupancy sensor. According to the characteristics of the target space, the energy saving rate was 3–50% in regularly occupied spaces and 46–86% in irregularly occupied spaces. In a study conducted in Calgary, Canada, Cabrera et al. [31] showed how energy waste patterns could be quantified and understood. The authors concluded that the lights were turned on in the absence of occupants for an average of 10.6 h per day and that if such waste could be avoided, energy savings of about 70% could be reached. Xu et al. [32] studied the energy performances of various lighting control systems in an office-type test bed. Among these systems, manually switched-on and automatically switched-off lighting control strategies showed energy savings of more than 30%, achieving the greatest energy savings. Mansur et al. [33] analyzed the effect of an occupancy lighting control system in the restrooms of university buildings. Fifty-eight motion sensors were installed in 30 restrooms, resulting in energy savings of about 77.5% per day, on average.

Time scheduling-based control systems reduce waste by turning off lights at preset times in regularly scheduled spaces and are cost-effective systems. Itani et al. [34] analyzed the energy savings achieved by one of these systems in an eight-storey building in Beirut, Lebanon. By controlling the lighting schedule, energy savings of approximately 11.8% were achieved. The system also reduced cooling loads at the same time, reducing the building's energy consumption by about 2.6%. Yang et al. [35] proposed a new time scheduling-based lighting control methodology based on a lighting control schedule derived from the recorded daily routines of the occupants. Gorgulu et al. [21] studied the energy saving potential for the outdoor lighting at the Istiklal Campus of Burdur Mehmet Akif Ersoy University, Burdur, Turkey. Four different scenarios, including time scheduling, dimming, and lighting replacement, were analyzed. Time scheduling saved the most energy for the least investment. The time schedule was set to turn off the lights 30 min after classes concluded, producing about 50% energy savings. Abas et al. [36] conducted a study on controlling air conditioners and lighting systems using programmable controllers. Lighting and air conditioning were turned off when no occupants were present or at the predetermined times. A classroom case study showed energy savings on the order of 35%.

Daylight-linked control systems are designed to conserve energy by monitoring the level of solar radiation with a light sensor. These systems can be classified according to the

type of illuminance measurement (closed-loop, open-loop) as well as the method used to control the lighting (on/off, dimming). A closed-loop system measures the illuminance, including light from the luminaires and solar radiation, and controls the lighting accordingly, whereas an open-loop system measures only solar radiation and controls the lighting based on the level of radiation [24]. The on/off method involves turning lights on/off in accordance with the measured illuminance value. The dimming control method manages the brightness of the lighting, keeping it between a minimum and maximum illuminance level. In [32,37], a daylight-on/off control system with a target illuminance of 250–300 lux was tested and produced energy savings of 25%. Shishegar et al. [24] investigated the effect of a daylight-linked control system on office buildings located in hot climates. Through simulations, different scenarios consisting of on/off control and dimming were evaluated. It was determined that energy consumption can be reduced by up to 85%, and total energy consumption can be reduced by approximately 30%. Moreover, according to various studies utilizing simulations and field surveys, daylight-linked control systems result in energy savings of about 11.2–69.6%, although deviations can occur, depending on the target illuminance [38–50]. According to previous research, the daylight-linked control systems have shown large variations in energy saving performance depending on system type and the environment. As a consequence, the deployment of these systems has been limited.

3. Methodology

This paper proposes a digital twin-based assessment framework for evaluating the lighting energy savings of various strategies for a university classroom, as shown in Figure 1. The framework consists of a digital twin model construction process that can mimic lighting system operations in an actual building. It defines an energy-saving strategy for a building and a decision-making process for using it. The framework's energy saving assessment process is described in detail in the section below.

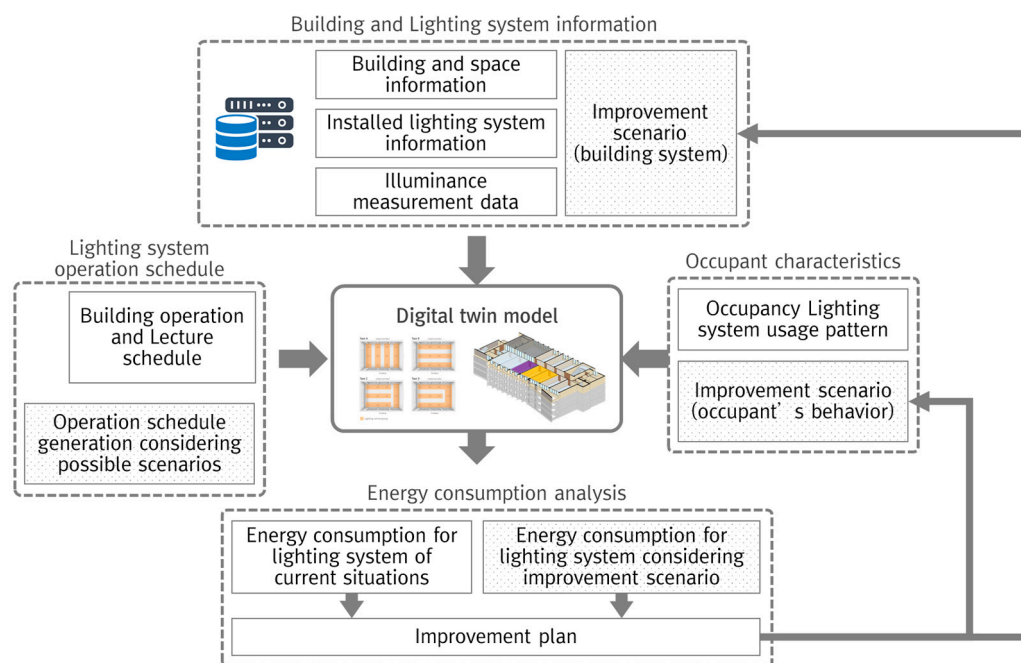


Figure 1. Flowchart of the proposed evaluation framework.

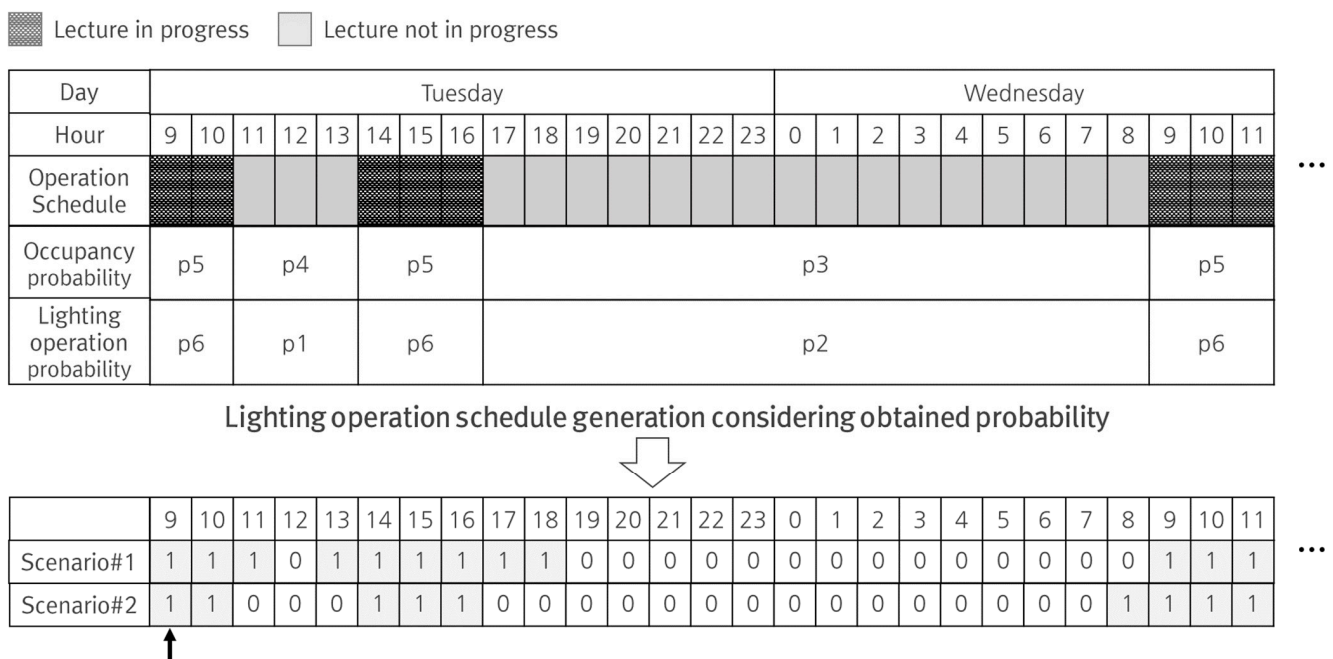
3.1. Digital Twin Building Process

The digital twin model for evaluating energy-saving strategies is built by integrating the physical environment of the building and a database defining the occupants, operation scenario, and field measurement data. The database on the physical environment contains system information, such as the number of lights, types and specifications of lights, power consumption, and control system as well as architectural information, such as outlines of

buildings, room compositions, size and shape of each room, and layout information for windows and walls. The building operation scenario includes information on the operating schedule of the building and the utilization rates of the classrooms. The database defining the occupants is a probabilistic model that reflects the operation schedule of the lighting system controlled by the occupants that are not considered in the operation design plan. A field measurement value is acquired to simulate the actual environment and to verify the virtual model; generally, the illuminance level (lux) is used.

3.2. Operating Schedule Generation

Figure 2 shows an example of the creation of an operating schedule for a lighting system that considers the planned lecture schedule for each day, weekend, and hour within the evaluation period.



Time step is based on the unit used in the lecture time table. it can be divide to several minutes for high-resolution analyses.

Figure 2. Probabilities for the occupancy and lighting operation.

The operating schedules of the lighting systems in individual lecture rooms are generated based on the lecture schedule. At this point, the operation times may vary, depending on the control system installed in the building or energy-saving mentalities of the occupants. According to a previous study [31], in the case of educational buildings, lights are on in the absence of occupants for 10.6 h a day. In such an environment, the extra hours of use vary depending on the application of PIR lighting and the energy-saving mentalities of the occupants. For example, after the last lecture planned in the classroom is over, the lighting system status (on/off) will depend on the occupants' behavior when leaving the room.

The proposed framework is designed to stochastically define and evaluate the variations in an operating schedule according to the existing control system and the level of occupant consciousness. To this end, it is necessary to define the probabilities listed below via CCTV monitoring or sample surveys of the target site.

- the probabilities of lighting system usage: p1 is the probability that the lighting system stays on during the break from the end of the allocated lecture to the start of the next lecture, p2 is the probability that the lighting system will stay on after the last lecture in the classroom, and p6 is the probability of lighting system usage during lectures.
- occupancy probabilities: p3 is the probability that the lights will stay on from the end of the last lecture to the start of the next day's first class, p4 is the probability that the

lights will stay on during breaks between classes, and p_5 is the probability that the lights will stay on during class.

3.3. Energy Saving Calculation

Table 1 shows the representative strategies that can be used for lighting energy savings. The energy-saving mechanisms that make up the strategy include increased efficiency of light sources, adjustments of illuminance levels, and reductions in surplus consumption (in the absence of occupants). When configuring the strategy, it is necessary to consider the application's target and effect.

Table 1. Representative energy saving strategies.

Mechanism	Strategy	Application Target		Effects		Ref.
		Light System	CONTROL SYSTEM	Operation Time	Energy Consumption	
Improvement in efficiency	Light source replacement	O	-	-	O	[12–22]
	Adjustment of the output of the luminaire	O	-	-	-	[23,29]
Adjustment of illuminance levels	Adjustment of the output of the luminaire	O	-	-	-	[23,29]
	Daylight-linked control system	O	O	-	O	[24,32,37]
Reduction of surplus consumption in the absence of occupant	Occupancy control system (PIR lights)	-	O	O	-	[13]
	Time scheduling by system	-	O	O	-	[34,35]
	Time scheduling by manager	-	-	O	-	

For example, if the strategy aims to replace light sources to improve energy efficiency, the lighting system is the target of the application, and a reduction in energy consumption is the effect of the application. The digital twin model, which integrates a database of physical building information, measured environments, operating scenarios, and probabilities of occupants' behavior, calculates the amount of energy savings by performing simulations reflecting improved light source specifications and operating schedules. Multiple strategies may be combined and applied to the same building.

The formulas with which the digital twin model calculates the energy savings of each strategy are shown in Equations (1) and (2). Here, Δt represents the time step that is set based on the unit used in the lecture timetable. Note that it can be set to several minutes for high-resolution analyses. The lighting operation time and light source energy consumption are reflected in $P_{t,i}$ and $LP_{t,i}$, respectively.

$$n = d \times 24 \times \frac{60}{\Delta t} \quad (1)$$

$$E_i = \frac{\Delta t}{60} \sum_{t=1}^n (P_{t,i} \times LP_{t,i}) \quad (2)$$

where n denotes the number of time steps, d is the number of days used for analysis, Δt [min] is the size of the time step, i is the classroom index, E_i [Wh] represents the electricity consumption of classroom i during d , t is the index of each time step, $P_{t,i}$ denotes the lighting operation probability of classroom i for time step t , and $LP_{t,i}$ [W] represents the power consumption of the lighting in classroom i for time step t .

4. Case Study

4.1. Description

A case study involving the classrooms for the entire engineering college at a university in Daegu, South Korea was conducted to test the framework proposed in Section 3. The analysis was conducted for one year. Universities have different lecture timetables each semester. Since schedule changes affect the lighting operation times of the classrooms, the analysis was also conducted by semester. The analysis was carried out for nine buildings of the target university. Table 2 shows the overview of the target site. Although the total number of analyzed classrooms is 55, there are differences in the number of classrooms where classes are conducted by semester. In the first semester, 54 classrooms (total area 4780.6 m²) were utilized, whereas in the second semester, 53 classrooms (total area 4770.08 m²) were analyzed.

Table 2. Overview of target site.

Bld. Code	No. of Classrooms	Avg. Area (m ² /Classroom)	Bld. Usage (%)		Power Consumption (W/m ²)	Illuminance on Desk (lux)
			1st Semester	2nd Semester		
401	8	106.3	53	53	7.5	1021
402	2	121.7	47	30	8.1	710
404	6	76.9	41	40	6.4	1085.6
406	6	81.7	44	43	6.3	776.5
408	6	103.7	44	45	7.3	937.3
409	8	68	36	37	13.3	1045.4
410	11	91.8	42	39	8.4	840.4
411	1	84	60	53	7.6	1183
419	7	83.6	44	38	9	1148
	55	90.9	45.7	42	8.2	971.9

4.1.1. Probability Estimation for Operation Scheduling

In order to apply the proposed framework, it is necessary to understand the human behavior associated with the use of lighting systems. For this purpose, the probability of classroom occupancy and the operation of lighting were used. Probabilities were derived by observing classroom 302 in engineering building 8, where CCTV was installed, and classes were conducted normally. The analysis was made based on classroom videos from 3–20 May 2018. Although the videos spanned 18 days, the final analysis used just 11 days' worth of video, as it excluded weekends and holidays when classes were not held. For these videos, lectures, occupancy, and lights on/off were checked every 30 min, and the following probabilities necessary for calculating energy consumption were derived.

- The probability of lights being on between classes ($p_1 = 0.5259$): This probability measures the percentage of time the lights were on during breaks between classes.
- The probability of lights being on between the end of the last class and the beginning of the first class on the following day ($p_2 = 0.6364$): In the target classrooms, an energy management plan was being applied, in which the manager turned off unnecessary lights around 6:00 P.M., the time when the last classes were over. Therefore, when determining p_2 , it was assumed that a manager did not exist. Thus, if the last person left the classroom without turning off the light after the last class, it was assumed that the light remained on until the first class of the next day.
- The probability of occupancy between the end of the last class and the beginning of the first class on the following day ($p_3 = 0.071$): This was derived as the percentage of occupancy time in the room between the end of the last class and the beginning of the first class on the following day.

- The probability of occupancy between classes ($p_4 = 0.4889$): The probability measured the chance of occupancy during the break between the end of a class and the start of the following class.
- Probability of occupancy during the class ($p_5 = 1$): It is not possible to conduct a class without occupancy. Thus, p_5 was assumed to be 1.
- The probability of lights being on during class ($p_6 = 1$): As a result of the field study, it was confirmed that most classes habitually turn the lights on, regardless of the amount of external sunlight. Therefore, p_6 was assumed to be 1.

4.1.2. Field Measurement of Illuminance Environment

In order to assess the degree of overdesign of the lighting in the target classrooms, an assessment of illuminance was necessary. The illuminance measurements were performed at night (19:00–23:00) to minimize the effects of solar radiation. The illuminance was measured at the height of the desks. A Testo 480 was used to measure the illuminance. This lux sensor meets the accuracy requirements in DIN EN 13032-1 and for class C, according to DIN 5032-7. Considering that the illuminance level may vary by location within a classroom, the illuminance was measured at three points for each classroom, and the median value was used as the illuminance value of the corresponding classroom. In university classrooms, the zone shapes and lighting arrangements often overlap. As a consequence, unnecessary procedures were omitted by applying the results for one classroom to similar classrooms.

Figure 3 shows the illuminance status for classrooms. All classrooms were overdesigned compared to the 500 lux recommendation in EN 12464-1 [23]. The average value of illuminance was about 967.5 lux, the maximum value was 1519 lux, the median value was 972 lux, and the minimum value was 523 lux. This problem occurred because the luminaire output had not been considered when fluorescent lamps were replaced with LEDs in the past.

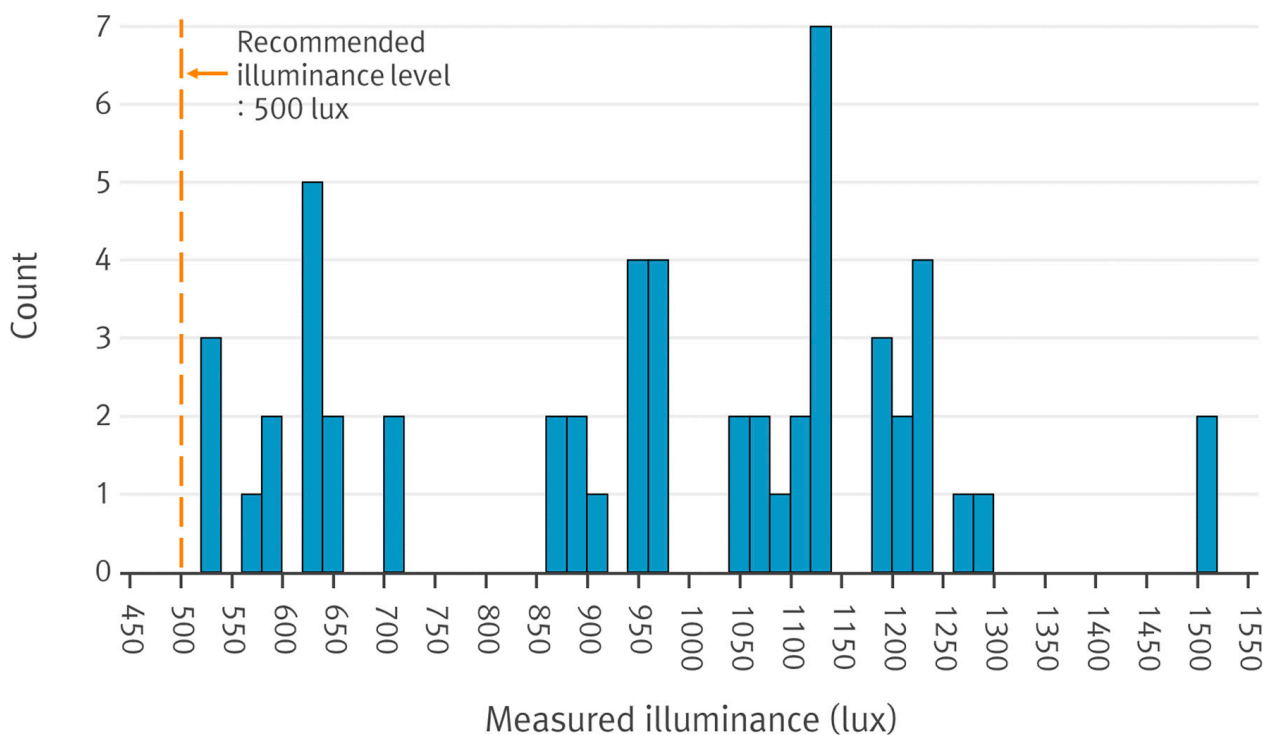


Figure 3. Histogram of the illuminance measurement values in the target classrooms.

4.1.3. Lighting Control System

In order to evaluate classroom energy consumption, it is necessary to investigate the lighting power consumption and the arrangement of lighting control groups. Figure 4 shows the power consumption distribution by classroom. The lowest power consumption was 240 W, the median value was 680 W, the average value was about 734.4 W, and the maximum value was 1492 W.

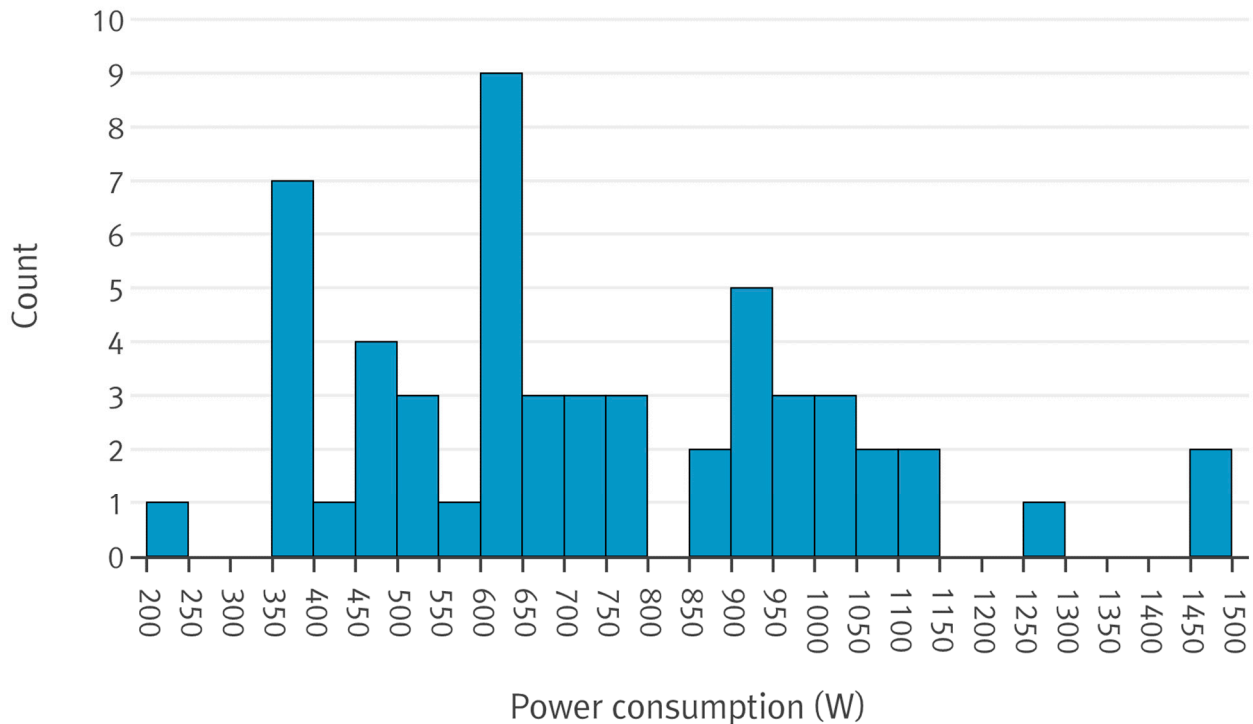


Figure 4. Histogram of the power consumption in the target classrooms.

The number of groups in which lighting was segmentally controlled and the forms of segmentation were investigated. The lights were arranged to be divided into control groups of at least 2, an average of about 3.9, and at most 8.

As a result of the investigation, it was possible to divide the lighting control groups into four types, as shown in Figure 5. Type A covered cases where the lighting control line was mainly parallel to the blackboard. Cases in which a small amount of indirect lighting not significantly affecting the classroom power consumption was placed in a direction perpendicular to the blackboard were also classified as Type A. In Type B, the lighting control groups were configured perpendicular to the blackboard. Type C covered cases where a mixed vertical and horizontal control group was used and the control line on the window side was individually controllable. Type D covered cases in which the vertical and horizontal control groups were mixed, but the control group on the window side was not individually controllable. In total, 55 classrooms were analyzed, of which 22 were of type A, 11 of type B, 10 of type C, and 12 of type D. In 21 classrooms (types B and C), individual control of the lighting group on the window side was possible; in the remaining 34 classrooms (types A and D), this type of control was not possible.

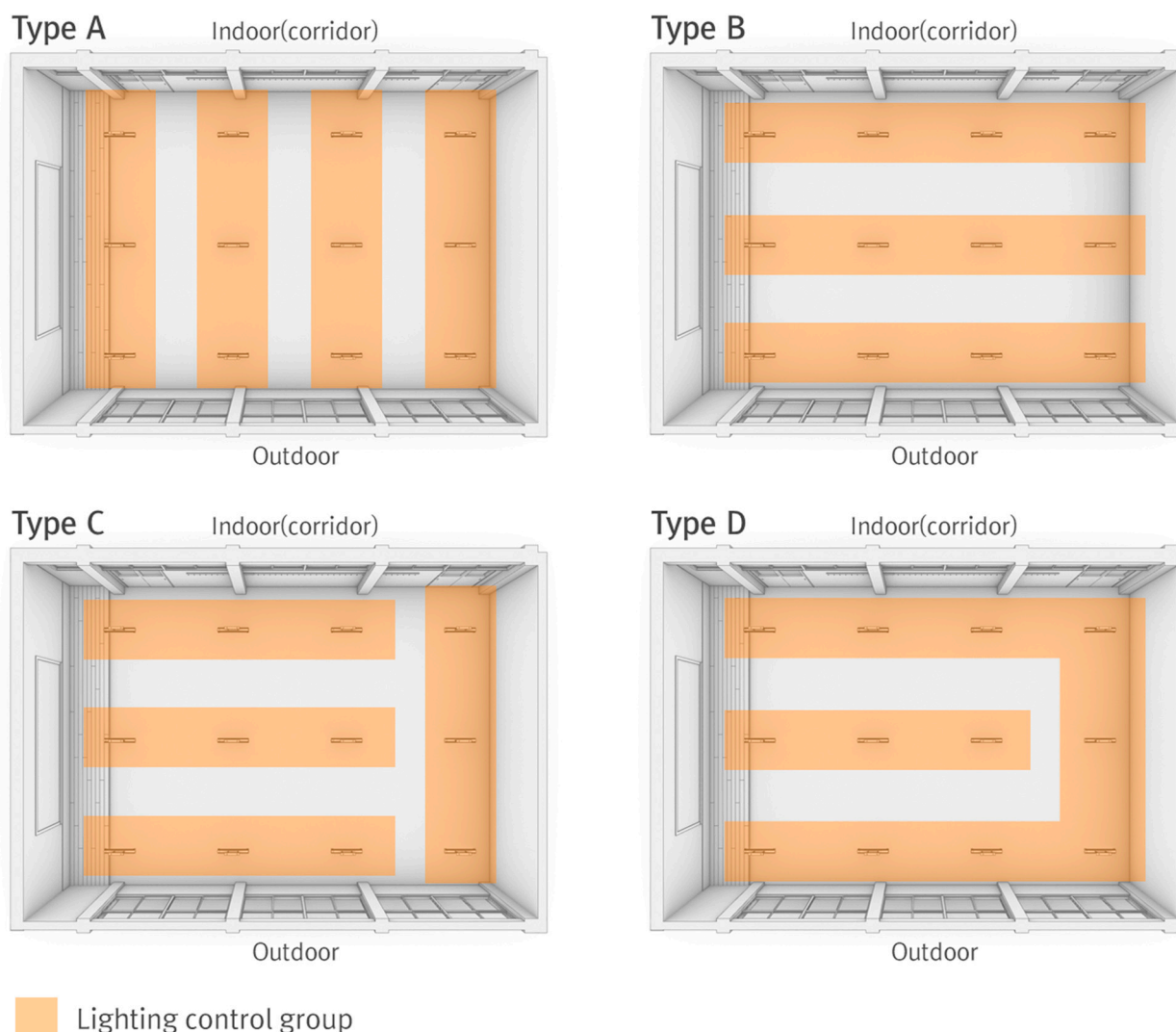


Figure 5. Types of lighting control groups.

The proposed framework derives the energy consumption based on the lecture timetable. In this case study, the lecture timetables were obtained from the university's computer system. In particular, timetables for the first and second semesters of 2018 for 55 classrooms were collected, and weekends and graduate classes held after 6 pm were excluded from the analysis.

The 54 classrooms analyzed in the first semester had an average usage rate of about 45%, a minimum of 13%, and a maximum of 76%. The usage rate indicates the ratio of the time used for classes out of the available time for lecture (from 9:00 A.M. to 6:00 P.M. or 45 h per week). The 53 classrooms in the second semester had an average usage rate of about 43%, a minimum of 7%, and a maximum of 89%, indicating large variations in the usage rate by classroom.

4.1.4. Scenario Definition

Scenarios for evaluating energy savings were established. The scenarios used in the study are based on a hypothetical scenario for replacement and maintenance of the lighting system in case study buildings. The scenarios are an empirical combination of real-world system deployment decisions. A total of nine scenarios were configured, including baseline, two scenarios related to on/off control, two scenarios related to quantitative adjustment, and four mixed scenarios. On/off control means switching all lights on or off. Quantitative

adjustment corresponds to quantitatively controlling illuminance, which is accomplished by reducing the illuminance of the luminaire or turning some group of lights on or off.

Each scenario was defined as follows.

- Baseline: In this case, no energy-saving measures are applied.
- Scenario 1. [On/off] manual control by a manager: At 18:00 when the last class ends, the building manager walks around each classroom and turns off the lights. Labor costs are involved, but additional equipment is not necessary. Energy is then not wasted after the last class when no classes are in session.
- Scenario 2. [On/off] PIR control: In this scenario, the lighting system is turned on when occupants are detected by the PIR sensor and turned off when occupants are not detected. PIR sensor installation is required, but it reduces energy waste during non-occupied time intervals.
- Scenario 3. [Quantitative adjustment] reducing illuminance: In the case of a classroom with over-designed lighting, lighting is replaced to adjust the illuminance level to the recommended level of 500 lux.
- Scenario 4. [Quantitative adjustment] control partial lighting groups: During the daytime when sunlight is sufficient, artificial lighting may be unnecessary near the windows. This method eliminates unnecessary energy consumption by turning off the lighting groups by the windows.
- Scenario 1 × 3. [On/off] manual control by a manager + [quantitative adjustment] reducing illuminance: Scenarios 1 and 3 are applied simultaneously. Illuminance is set to the recommended level, and unnecessary lighting is turned off by the manager at 6 P.M.
- Scenario 1 × 4. [On/off] manual control by a manager + [quantitative adjustment] control partial lighting groups: Both scenarios 1 and 4 are applied simultaneously. The lighting control groups by windows are turned off when there is sufficient sunlight, and all unnecessary lights are turned off by the manager at 6 P.M.
- Scenario 2 × 3. [On/off] PIR control + [quantitative adjustment] reducing illuminance: Scenarios 2 and 3 are applied simultaneously. The illuminance level is adjusted to the recommended value, and the lights are turned on only when the PIR sensor detects occupants.
- Scenario 2 × 4. [On/off] PIR control + [quantitative adjustment] control partial lighting groups: Scenarios 2 and 4 are applied simultaneously. Through the PIR sensor, the lighting is turned on only when occupants are present, and unnecessary lighting by windows is turned off when there is sufficient sunlight.

The energy consumption in each scenario was derived through the following calculation process. All calculations were performed in time steps of 30 min (the time step used in the lecture timetable).

In the baseline scenario, the probability of the lighting operation is determined based on whether each time step contains a lecture or not. If a lecture is in progress at the corresponding time step, the lights are on with probability p_6 . If the corresponding time step contains a break between classes, the lights are on with probability p_1 . For time steps between the end of the last class and the beginning of the first class on the following day, the lights are on with probability p_2 . When the lighting operation probability for all time steps has been determined according to the above rules, the energy consumption for each time step is derived from the power consumption information gathered from the field study and the lighting operation probability. If, for example, the lighting operation probability is 50% at a time step and the power consumption is 1000 W, 250 Wh of power is consumed during the 30-min time interval. Lastly, the cumulative energy consumption is derived by adding up the energy consumptions of the time steps.

In scenario 1, it is assumed that the manager turns off unnecessary lights at 6 P.M., the time when almost all classes have ended. The calculation flow is the same as for the baseline. However, scenario 1 is divided into the following three cases, depending on when the last class ends. When the last class ends before 6 pm, the lights will be on with

probability p_2 (about 63.64%) from the end of the last class to 6 P.M. After 6 P.M., the lights will have been turned off by the manager. When the last class ends at 6 P.M., the lights will be turned off between 6 pm and the start of the first class on the following day. If the last class ends after 6 P.M., the manager cannot control the lights because classes are in progress. In this case, the lighting operation time before the first class on the following day is set based on p_2 , as in the baseline.

In scenario 2, the occupancy probability is used to determine whether the lighting system is on. Therefore, it is important to derive the appropriate occupancy probability for each situation. According to the probabilities derived earlier, the lights are always on during class ($p_5 = 1$). In other cases, the occupancy probability is determined based on the probability (p_4, p_3) appropriate for the situation. In analyzing this scenario, detailed factors that do not significantly affect energy consumption, such as the reaction speed of the PIR sensor, are not considered. That is, it is assumed that the occupancy probability and the lighting operation probability are the same. The process used after the occupancy and lighting operation probabilities are derived for each time step is the same as that used for the baseline scenario.

The lighting control method in scenario 3 is the same as that of the baseline. However, in order to calibrate the illuminance to the recommended level, the power consumption of the lighting is reduced. The target classrooms of this case study use LEDs. Therefore, the analysis was conducted assuming that the illuminance level and lighting power consumption are in direct proportion. For example, if the power consumption of a classroom with a 1000 lux illuminance level at the working surface is 800 W, it is assumed that in order to reduce the illuminance to the recommended level of 500 lux, the power consumption must also be reduced by half to 400 W. If the lighting operation probability for each time step is determined using the same procedure used in the baseline scenario, then the energy consumption is calculated using the adjusted power consumption.

In scenario 4, it must first be determined whether the lighting control groups by the windows can be individually controlled. In this case study, a field study was conducted for this purpose, and it was determined that individual control was possible in 21 classrooms (types B, C) out of a total of 55 classrooms. For the other 34 classrooms, it was assumed that the lighting was operated in the same manner as in the baseline scenario. In the case of a classroom with partial control, it was determined empirically that the sunlight was sufficient from 9:00 to 13:00, so during that time period, turning the lights off at the window side would not disrupt the lecture. In the absence of partial group control, the energy consumption is derived in the same manner as in the baseline scenario, whereas in time steps where partial group control is applied, energy consumption is derived based on power consumption when the lighting groups by the windows are turned off.

Where on/off control and quantitative adjustment are mixed, the methods applied in the individual scenarios are applied simultaneously. For example, when scenarios 1 and 3 are applied together, the final energy consumption is derived using the lighting operation time reflecting manual control by the manager (scenario 1), and the reduced power consumption is derived from scenario 3.

4.2. Results

In this case study, the energy consumption patterns of nine scenarios were analyzed. Since the lecture timetable of the university was repeated weekly, the analysis results for each scenario were also derived and compared on a weekly basis.

Table 3 shows the total energy consumptions of the target classrooms by semester. In the case study, the lecture timetable varied by semester and so did the energy consumption. According to the analysis results, the on/off control method (scenarios 1 and 2) provided better energy savings (by at least 15%) than the quantitative adjustment method (scenarios 3 and 4).

Table 3. Electric power consumption by scenario.

Scenario	First Semester (<i>n</i> = 54)			Second Semester (<i>n</i> = 53)		
	Power Consumption (kWh/Week)	Energy Use Intensity (kWh/m ² ·Week)	Energy Saving Rate (%)	Power Consumption (kWh/Week)	Energy Use Intensity (kWh/m ² ·Week)	Energy Saving Rate (%)
Baseline	3295.684	0.689	0.000	3273.937	0.686	0.000
Scenario 1	1256.707	0.263	61.868	1229.128	0.258	62.457
Scenario 2	1214.505	0.254	63.149	1173.580	0.246	64.154
Scenario 3	1772.259	0.371	46.225	1755.077	0.368	46.392
Scenario 4	3237.885	0.677	1.754	3219.132	0.675	1.674
Scenario 1 × 3	673.506	0.141	79.564	659.019	0.138	79.871
Scenario 1 × 4	1218.200	0.255	63.037	1196.035	0.251	63.468
Scenario 2 × 3	644.753	0.135	80.436	625.303	0.131	80.901
Scenario 2 × 4	1178.306	0.246	64.247	1141.698	0.239	65.128

Among the on/off control methods, the method applying the PIR sensor showed better energy saving potential than manual control by the manager. However, the difference in the saving rate was about 1–2%, which is not significant. Therefore, the selection of a PIR sensor or manual control on the part of the manager should be made according to the target building. For example, if a university has a building manager, the additional energy savings obtained by installing PIR sensors would be insufficient to justify the cost of the sensors. When a manager is present, it is most cost effective to turn the lights off once a day after the last class is over.

Among the quantitative adjustment methods, scenario 3, which reduces the illuminance level, showed about 44% more energy savings than scenario 4. In this case study, the lighting tended to be over-designed, as evidenced by the field study. As a result, the energy savings were large due to the reduction in illuminance. On the other hand, scenario 4 produced energy savings of 1–2%. In this case study, partial control of the lighting groups by the windows was possible in only 21 classrooms (about 38% of the 55 classrooms). With the window-side lights turned off in 21 classrooms, the average power consumption was reduced by 27.8%. However, since the time period during which the window-side lights could be turned off (9:00 to 13:00) included the lunch period (12:00 to 13:00), energy savings were possible for only 3 h, so the effect was not significant. Hence, for scenario 4, the energy savings will vary greatly depending on the type of lighting arrangement, the lecture timetable, and the amount of solar radiation coming through the windows.

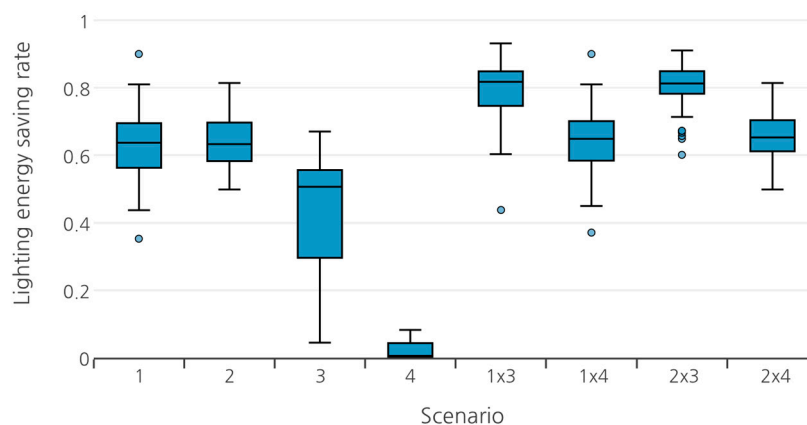
Figure 6 shows the box plots of the energy saving rates for the scenarios. There were no significant differences by semester in the energy saving distributions by classroom, and the scenarios produced similar energy saving distributions.

In scenario 3, the energy saving rate varies greatly depending on the degree to which the existing lighting is overdesigned for each classroom. As an example, when the illuminance level (1519 lux) of the lecture room with the most overdesigned lighting was reduced to 500 lux, energy consumption decreased by about 67% compared to the baseline. However, in the classroom where the measured illuminance level was the lowest at 523 lux, energy savings were only about 4.4%, even once illuminance was adjusted to the recommended level.

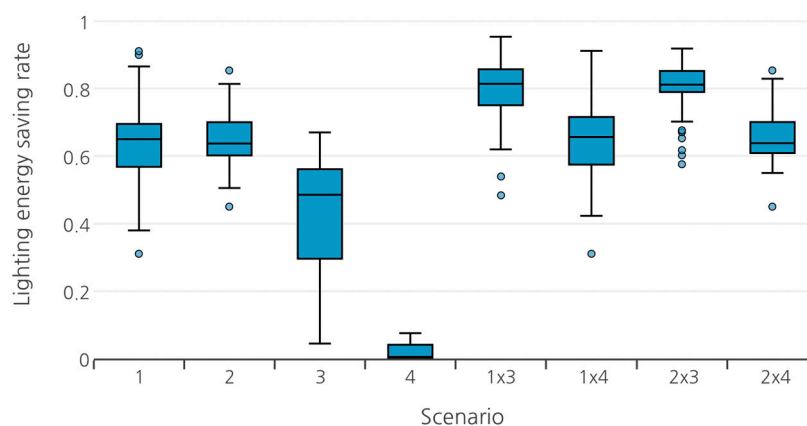
In scenario 4, a maximum of about 7–8% and a minimum of 0% in energy were saved depending on the classroom, and the scenario had the lowest energy savings and deviation among the analyzed scenarios.

A managerial strategy can be derived from the results of the analysis. Turning off lights after the last class has a major impact on energy consumption in educational buildings. Therefore, it is very important to install the PIR system or have the manager turn the lights off. However, in a building with a high usage rate because of many lectures, only little wasted factor exists with the idle time between lectures, so the difference in savings between the PIR system and manual lights off by the student or manager is only 2%. Many

universities, including the case study target, have energy saving activity programs linked with student scholarship which includes occupant awareness of lights-out. The manager can use the budget to improve the awareness of the occupants instead of the additional energy saving of 2% that can be obtained by introducing the new PIR sensor.



(a)



(b)

Figure 6. Box plots of energy savings for the scenarios: (a) first semester ($n = 54$); (b) second semester ($n = 53$).

5. Conclusions

The importance of energy management is currently being emphasized, and the energy saving potential in lighting is very high in educational buildings. Because various technologies and strategies can be used to save energy, providing a tool that can quantify and assess the lighting energy saving potential of these various strategies can be helpful.

In this paper, a digital twin-based assessment framework for lighting energy-saving strategies in educational buildings was proposed. In addition, a digital twin model was created for 55 classrooms across nine buildings in an engineering college at a university in South Korea, and the energy saving potentials of four energy saving strategies were analyzed and reported.

In the target classrooms, the lights were turned on when there were no occupants for an average of 10.7 h per day. Accordingly, turning lighting systems off through PIR sensors

or a manager after the end of the last class produced energy savings of more than 60%. There was a difference of only 1.3% in the energy saving rate produced by a PIR system accompanied by system replacement and manual control by the manager at a preset time. Thus, it seems that energy can be saved with minimal investment and without replacing the existing lighting system by introducing time scheduling-based lighting control.

In addition, the LED lighting in most classrooms was found to be overdesigned, indicating that energy savings of 46% can be achieved when the illuminance is adjusted to an appropriate level. On the other hand, in the case of a partial on/off strategy for window-side lighting groups, energy savings of only 7–8% were achieved. Thus, the existing lighting system should be replaced because of the lack of proper lighting control group design.

In the case study, energy consumptions of the combined scenario were calculated and compared considering the required utility level and system application. However, various indicators such as cost for system introduction and subjective satisfaction of occupants were not considered. This aspect will be addressed in an advanced future study.

The decision support system integrating digital twins can further help designer and operator in defining the optimal design/control strategy. Digital twin based decision making is expected to be applied to design a system and control industrial environments such as residential lighting and factory facilities. To this end, utility requirements for various building environments and databases for system configurations need to be developed in future study.

Author Contributions: H.S. supervised the work and performed conceptualization, prepared the methodologies, performed the experiments, and validated the model, while W.-S.Y. prepared the first draft, completed the writing process, and carried out formal analysis. All authors have read and agreed to the published version of the manuscript.

Funding: The APC was funded by the Human Resources Program in Energy Technology of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) granted financial resource from the Ministry of Trade, Industry & Energy, Korea (No.20204010600060).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (No.2020R1C1C1007127). This work was supported by the Human Resources Program in Energy Technology of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) granted financial resource from the Ministry of Trade, Industry & Energy, Korea (No.20204010600060).

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

References

1. Beiter, P.; Elchinger, M.; Tian, T. *2016 Renewable Energy Data Book*; National Renewable Energy Lab. (NREL): Golden, CO, USA, 2017.
2. Friedrich, S. Energy Efficiency in Buildings in EU Countries. *CESifo DICE Rep.* **2013**, *11*, 57–59.
3. 2021 Global Status Report for Buildings and Construction | Globalabc. Available online: <https://globalabc.org/resources/publications/2021-global-status-report-buildings-and-construction> (accessed on 18 March 2022).
4. Yu, P.C.H.; Chow, W.K. A Discussion on Potentials of Saving Energy Use for Commercial Buildings in Hong Kong. *Energy* **2007**, *32*, 83–94. [[CrossRef](#)]
5. Hermoso Orzáez, M.J.; de Andrés Díaz, J.R. Comparative Study of Energy-Efficiency and Conservation Systems for Ceramic Metal-Halide Discharge Lamps. *Energy* **2013**, *52*, 258–264. [[CrossRef](#)]
6. Di Stefano, J. Energy Efficiency and the Environment: The Potential for Energy Efficient Lighting to Save Energy and Reduce Carbon Dioxide Emissions at Melbourne University, Australia. *Energy* **2000**, *25*, 823–839. [[CrossRef](#)]
7. Beccali, M.; Bonomolo, M.; Ciulla, G.; Galatioto, A.; Lo Brano, V. Improvement of Energy Efficiency and Quality of Street Lighting in South Italy as an Action of Sustainable Energy Action Plans. The Case Study of Comiso (RG). *Energy* **2015**, *92*, 394–408. [[CrossRef](#)]

8. Energy Information Administration (EIA). Commercial Buildings Energy Consumption Survey (CBECS). Available online: <https://www.eia.gov/consumption/commercial/> (accessed on 18 March 2022).
9. 2015 U.S. Lighting Market Characterization. Available online: <https://www.energy.gov/eere/ssl/downloads/2015-us-lighting-market-characterization> (accessed on 18 March 2022).
10. Lizana, J.; Serrano-Jimenez, A.; Ortiz, C.; Becerra, J.A.; Chacartegui, R. Energy Assessment Method towards Low-Carbon Energy Schools. *Energy* **2018**, *159*, 310–326. [[CrossRef](#)]
11. Kim, J.-S.; Lee, K.-B.; Lee, I.-H.; Kim, S.-D. Analysis of Energy Consumption Pattern and Greenhouse Gas Emission in the Academic Facility. *J. Korean Soc. Environ. Eng.* **2012**, *34*, 604–612. [[CrossRef](#)]
12. Mahlia, T.M.I.; Razak, H.A.; Nursahida, M.A. Life Cycle Cost Analysis and Payback Period of Lighting Retrofit at the University of Malaya. *Renew. Sustain. Energy Rev.* **2011**, *15*, 1125–1132. [[CrossRef](#)]
13. Dubois, M.C.; Gentile, N.; Bisegna, F.; Knoop, M.; Matusiak, B.; Osterhaus, W.; Stoffer, S.; Tetri, E. Daylighting and Lighting Retrofit to Reduce Energy Use in Non-Residential Buildings: A Literature Review; IEA SHC Task 50; 2016. Available online: https://task50.iea-shc.org/Data/Sites/1/publications/Technical_Report_T50_D2_final.pdf (accessed on 2 February 2022).
14. Mahlia, T.M.I.; Said, M.F.M.; Masjuki, H.H.; Tamjis, M.R. Cost-Benefit Analysis and Emission Reduction of Lighting Retrofits in Residential Sector. *Energy Build.* **2005**, *37*, 573–578. [[CrossRef](#)]
15. Clarke-Sather, A.; Li, Y.; Qu, J. Lighting Energy Use in Anding District, Gansu Province, China. *Energy Sustain. Dev.* **2016**, *32*, 40–49. [[CrossRef](#)]
16. Bonomolo, M.; Baglivo, C.; Bianco, G.; Maria Congedo, P.; Beccali, M. Cost Optimal Analysis of Lighting Retrofit Scenarios in Educational Buildings in Italy. *Energy Procedia* **2017**, *126*, 171–178. [[CrossRef](#)]
17. Berardi, U.; Manca, M.; Casaldaliga, P.; Pich-Aguilera, F. From High-Energy Demands to NZEB: The Retrofit of a School in Catalonia, Spain. *Energy Procedia* **2017**, *140*, 141–150. [[CrossRef](#)]
18. Josijevec, M.; Gordic, D.; Milovanovic, D.; Jurisevic, N.; Rakic, N. A Method to Estimate Savings of Led Lighting Instalation in Public Buildings: The Case Study of Secondary Schools in Serbia. *Therm. Sci.* **2017**, *21*, 2931–2943. [[CrossRef](#)]
19. Gamarra, A.R.; Istrate, I.R.; Herrera, I.; Lago, C.; Lizana, J.; Lechón, Y. Energy and Water Consumption and Carbon Footprint of School Buildings in Hot Climate Conditions. Results from Life Cycle Assessment. *J. Clean. Prod.* **2018**, *195*, 1326–1337. [[CrossRef](#)]
20. Mohammadalizadehkorde, M.; Weaver, R. Quantifying Potential Savings from Sustainable Energy Projects at a Large Public University: An Energy Efficiency Assessment for Texas State University. *Sustain. Energy Technol. Assess.* **2020**, *37*, 100570. [[CrossRef](#)]
21. Gorgulu, S.; Kocabey, S. An Energy Saving Potential Analysis of Lighting Retrofit Scenarios in Outdoor Lighting Systems: A Case Study for a University Campus. *J. Clean. Prod.* **2020**, *260*, 121060. [[CrossRef](#)]
22. Booyesen, M.J.; Samuels, J.A.; Grobbelaar, S.S. LED There Be Light: The Impact of Replacing Lights at Schools in South Africa. *Energy Build.* **2021**, *235*, 110736. [[CrossRef](#)]
23. Baker, C.S. A Bright Future: Market Transformation in Texas Lighting Efficiency Incentive Programs. *Energy Eng.* **2013**, *110*, 35–46. [[CrossRef](#)]
24. Shishegar, N.; Boubekri, M. Quantifying Electrical Energy Savings in Offices through Installing Daylight Responsive Control Systems in Hot Climates. *Energy Build.* **2017**, *153*, 87–98. [[CrossRef](#)]
25. Carli, R.; Dotoli, M. A Dynamic Programming Approach for the Decentralized Control of Energy Retrofit in Large-Scale Street Lighting Systems. *IEEE Trans. Autom. Sci. Eng.* **2020**, *17*, 1140–1157. [[CrossRef](#)]
26. Beccali, M.; Bonomolo, M.; Brano, V.L.; Ciulla, G.; Di Dio, V.; Massaro, F.; Favuzza, S. Energy Saving and User Satisfaction for a New Advanced Public Lighting System. *Energy Convers. Manag.* **2019**, *195*, 943–957. [[CrossRef](#)]
27. Khajavi, S.H.; Motlagh, N.H.; Jaribion, A.; Werner, L.C.; Holmström, J. Digital Twin: Vision, Benefits, Boundaries, and Creation for Buildings. *IEEE Access* **2019**, *7*, 147406–147419. [[CrossRef](#)]
28. Tao, F.; Zhang, H.; Liu, A.; Nee, A.Y. Digital Twin in Industry: State-of-the-Art. *IEEE Trans. Ind. Inform.* **2018**, *15*, 2405–2415. [[CrossRef](#)]
29. De Normalisation, C.E. EN 12464-1: Light and Lighting—Lighting of Work Places, Part 1: Indoor Work Places. *Com. Eur. Norm.* **2002**. Available online: https://www.ahjzu.edu.cn/_upload/article/files/50/b5/4e0248ef47278e4dead0447bd16a/89a6cb4c-2303-42e6-97a3-34d8adc7a5eb.pdf (accessed on 2 February 2022).
30. Richman, E.E.; Dittmer, A.L.; Keller, J.M. Field Analysis of Occupancy Sensor Operation: Parameters Affecting Lighting Energy Savings. *J. Illum. Eng. Soc.* **1996**, *25*, 83–92. [[CrossRef](#)]
31. Motta Cabrera, D.F.; Zareipour, H. Data Association Mining for Identifying Lighting Energy Waste Patterns in Educational Institutes. *Energy Build.* **2013**, *62*, 210–216. [[CrossRef](#)]
32. Xu, L.; Pan, Y.; Yao, Y.; Cai, D.; Huang, Z.; Linder, N. Lighting Energy Efficiency in Offices under Different Control Strategies. *Energy Build.* **2017**, *138*, 127–139. [[CrossRef](#)]
33. Mansur, T.M.N.T.; Ali, R.; Baharudin, N.H.; Ananda-Rao, K. Performance Analysis of Smart Lighting Control System for Sustainable Campus Operation. *Int. J. Adv. Technol. Eng. Explor.* **2021**, *8*, 54–63. [[CrossRef](#)]
34. Itani, T.; Ghaddar, N.; Ghali, K. Strategies for Reducing Energy Consumption in Existing Office Buildings. *Int. J. Sustain. Energy* **2013**, *32*, 259–275. [[CrossRef](#)]
35. Yang, H.; Lee, H. Lighting Scheduling for Energy Saving in Smart House Based on Life Log Data. *Procedia Environ. Sci.* **2014**, *22*, 403–413. [[CrossRef](#)]

36. Abas, M.F.; Saad, N.M.D.; Ramli, N.L. A Smart GUI Based Air-Conditioning and Lighting Controller for Energy Saving in Building. In Proceedings of the 8th WSEAS International Conference on Circuits, Systems, Electronics, Control & Signal Processing, Puerto De La Cruz, Spain, 14–16 December 2019; World Scientific and Engineering Academy and Society (WSEAS): Stevens Point, WI, USA, 2009; pp. 87–92.
37. Gunay, H.B.; O'Brien, W.; Beausoleil-Morrison, I.; Gilani, S. Development and Implementation of an Adaptive Lighting and Blinds Control Algorithm. *Build. Environ.* **2017**, *113*, 185–199. [[CrossRef](#)]
38. Boscarino, G.; Moallem, M. Daylighting Control and Simulation for LED-Based Energy-Efficient Lighting Systems. *IEEE Trans. Ind. Inform.* **2016**, *12*, 301–309. [[CrossRef](#)]
39. Chew, I.; Kalavally, V.; Oo, N.W.; Parkkinen, J. Design of an Energy-Saving Controller for an Intelligent LED Lighting System. *Energy Build.* **2016**, *120*, 1–9. [[CrossRef](#)]
40. Koroglu, M.T.; Passino, K.M. Illumination Balancing Algorithm for Smart Lights. *IEEE Trans. Control Syst. Technol.* **2014**, *22*, 557–567. [[CrossRef](#)]
41. Wagiman, K.R.; Abdullah, M.N. Intelligent Lighting Control System for Energy Savings in Office Building. *Indones. J. Electr. Eng. Comput. Sci.* **2018**, *11*, 195–202. [[CrossRef](#)]
42. Kandasamy, N.K.; Karunakaran, G.; Spanos, C.; Tseng, K.J.; Soong, B.-H. Smart Lighting System Using ANN-IMC for Personalized Lighting Control and Daylight Harvesting. *Build. Environ.* **2018**, *139*, 170–180. [[CrossRef](#)]
43. Li, D.H.W.; Lam, T.N.T.; Wong, S.L. Lighting and Energy Performance for an Office Using High Frequency Dimming Controls. *Energy Convers. Manag.* **2006**, *47*, 1133–1145. [[CrossRef](#)]
44. To, D.W.T.; Sing, L.K.; Chung, T.; Leung, C. Potential Energy Saving for a Side-Lit Room Using Daylight-Linked Fluorescent Lamp Installations. *Light. Res. Technol.* **2002**, *34*, 121–132. [[CrossRef](#)]
45. Koyle, B.; Papamichael, K. Dual-Loop Photosensor Control Systems: Reliable, Cost-Effective Lighting Control for Skylight Applications. In Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings, (ASSE' 10), Pacific Grove, CA, USA, 15–20 August 2010; pp. 157–166.
46. Delvaeye, R.; Ryckaert, W.; Stroobant, L.; Hanselaer, P.; Klein, R.; Breesch, H. Analysis of Energy Savings of Three Daylight Control Systems in a School Building by Means of Monitoring. *Energy Build.* **2016**, *127*, 969–979. [[CrossRef](#)]
47. Doulos, L.T.; Kontadakis, A.; Madias, E.N.; Sinou, M.; Tsangrassoulis, A. Minimizing Energy Consumption for Artificial Lighting in a Typical Classroom of a Hellenic Public School Aiming for near Zero Energy Building Using LED DC Luminaires and Daylight Harvesting Systems. *Energy Build.* **2019**, *194*, 201–217. [[CrossRef](#)]
48. Bernardo, H.; Antunes, C.H.; Gaspar, A.; Pereira, L.D.; da Silva, M.G. An Approach for Energy Performance and Indoor Climate Assessment in a Portuguese School Building. *Sustain. Cities Soc.* **2017**, *30*, 184–194. [[CrossRef](#)]
49. de Rubeis, T.; Muttillio, M.; Pantoli, L.; Nardi, I.; Leone, I.; Stornelli, V.; Ambrosini, D. A First Approach to Universal Daylight and Occupancy Control System for Any Lamps: Simulated Case in an Academic Classroom. *Energy Build.* **2017**, *152*, 24–39. [[CrossRef](#)]
50. Yu, X.; Su, Y.; Chen, X. Application of RELUX Simulation to Investigate Energy Saving Potential from Daylighting in a New Educational Building in UK. *Energy Build.* **2014**, *74*, 191–202. [[CrossRef](#)]