# Verification and Configuration of an Intelligent Lighting System Using BACnet

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***Abstract*—We have been engaged in the development and research of an intelligent lighting system, which allows both improving comfort of office workers and reducing power consumption. The results of our demonstration experiments in a real office environment showed that an intelligent lighting system is effective. Consequently, it is required to consider the introduction and operation of an intelligent lighting system. In a current intelligent lighting system, it has to be constructed for each office as it needs to be configured by creating a unique network. In addition, lighting control methods differ by vendors and a system needs to be configured differently for each vendor. For these reasons, there are problems in introducing and operating an intelligent lighting system in a large-scale environment. We thus propose an intelligent lighting system configured by using the BACnet communication protocol, which has increasingly spread in recent years, for the purpose of making it easier to introduce and operate an intelligent lighting system. Our verification experiments and simulation showed that an intelligent lighting system configuration using BACnet was effective.**

***Keywords–office lighting; lighting control; BACnet.***

## I. INTRODUCTION

In recent years, many researches have been conducted about the effects of the lighting of the office building on office workers [2]. It is expected that office worker's intellectual productivity, creativity and comfort are improved by working in their preferred light brightness[1].

In addition, energy conservation of office buildings have been promoted. However, in many cases, the lighting is brighter than what the office workers prefer, or unnecessary places are lit. It is possible to reduce the power consumption by improving the lighting environment. Against such a backdrop, we have focused on office lighting environment and proposed an intelligent lighting system that provides illuminance to individual office workers which they request, in minimal power consumption [4]. An intelligent lighting system is recognized as being useful and demonstration experiments have been carried out at 10 locations in Japanese office [3]. When an intelligent lighting system has been introduced, we confirmed that the power consumption is reduced by about 50% compared to the nomal office. In the future, we need to consider the spread of an intelligent lighting system and the operation and deployment in large-scale environment. A current intelligent lighting system is connecting to the dimmable lighting fixtures and a control computer in the network of each office.

Further, the control method of the lighting is different for each vendor. It is necessary to configure the suitable system of lighting control method for each vendor. In addition, with such a system configuration, a control computer is required for each office in which the system is installed. From these things, a current intelligent lighting system has issues in its diffusion to common offices, as well as in its implementation and operation in a large-scale environment. In order to solve these issues, we propose an intelligent lighting system using BACnet, which has been spreading increasingly to office buildings in recent years.

BACnet is a network protocol for office buildings. BACnet provides mechanisms for computerized building automation devices to exchange information, regardless of the particular building service they perform. Constructing an intelligent lighting system via BACnet enables centralized control without dependance on lighting control methods of different vendors. As it eliminates the necessity to install and individually control a control computer in each office, it makes the implementation and operation of an intelligent lighting system easy. Also, BACnet has already been used to control lighting in advanced office buildings. Therefore, it is possible to utilize the lighting apparatus in the office. For that reason, it is not necessary to do the improvement work when when we introduce an intelligent lighting system. This study thus constructed an intelligent lighting system using BACnet that can be implemented in an office building already controlling lighting by BACnet and examined its effectiveness and issues.

In Section 2, we describe an intelligent lighting system that we have proposed. In Section 3, we describe an intelligent lighting system using BACnet. In Section 4, we describes the issues of BACnet type intelligent lighting system. In Section 5, we build the BACnet type intelligent lighting system and perform an operation experiment. In Section 6, we perform a simulation assuming the large scale office environment to solve the issues shows in Section 4.

## II. INTELLIGENT LIGHTING SYSTEM

In this section, we describe an intelligent lighting system that we have proposed. First, we describes the outline of an intelligent lighting system. Second, we describes the algorithm of an intelligent lighting system. Finally, we describe the issues of an intelligent lighting system in a large scal office environment.

### A. *Outline and Configuration of an Intelligent LIghting System*

An intelligent lighting system realizes illuminance desired by each worker while minimizing energy consumption by changing the luminous intensity of lighting fixtures. An intelligent lighting system, as indicated in Fig. 1, is composed of a control computer, illuminance sensors, and electrical power meter, with each element connected via a IP network. A Control computer varies the luminance of each lighting fixture using an optimization method on the basis of the illuminance information and the power consumption information. It is thereby possible to achieve the illuminance desired by each worker with low power consumption.

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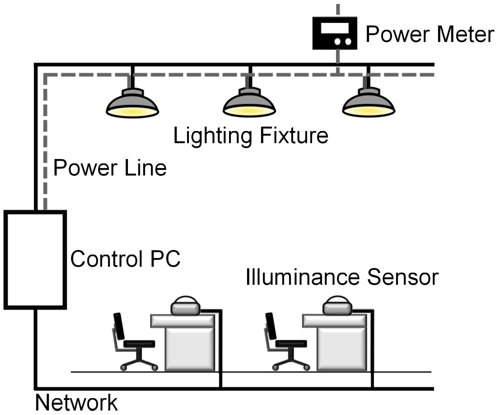


Figure 1. Configuration of The Intelligent Lighting System

### B. Control Algorithm of Intelligent Lighting System

In an intelligent lighting system, the ANA/RC(Adaptive Neighborhood Algorithm using Regression Coefficient) which is improved algorithm of SA(Simulated Annealing) for lighting control is used to control luminance intensity for each lighting fixture [5].

It is possible with ANA/RC to provide the target illuminance with minimum power consumption by making luminance intensity for lighting fixtures the design variable and by using the difference between the current illuminance and target illuminance as well as power consumption as objective functions. Furthermore, by learning the influence of each lighting fixture on each illuminance sensor using the regression analysis and by changing the luminance intensity depending on the results, rtly change to the optimal luminance intensity. This algorithm is effective to solve the problem, which the objective function is near monomodal function and changes in real time. The objective function is indicated in the (1).

As indicated in (1), the objective function $f$ consists of power consumption and illuminance constraint. Also, changing weighting factor $w$ enables changes in the order of priority for electrical energy and illuminance constraint. The illuminance constraint brings current illuminance to target illuminance or greater, as indicated by formula.

$$f_i = P + \omega \times \sum_{j=1}^{n} g_{ij} \quad (1)$$

$$g_{ij} = \begin{cases} 0 & (Ic_j - It_j) \geq 0 \\ R_{ij} \times (Ic_j - It_j)^2 & (Ic_j - It_j) < 0 \end{cases}$$

$$R_{ij} = \begin{cases} r_{ij} & r_{ij} \geq T \\ 0 & r_{ij} < T \end{cases}$$

$i$:lighting ID , $j$:illuminance sensor ID, $P$:power consumption [W], $\omega$:weight[W/lx$^2$]
$Ic$:current illuminance [lx], $It$:target illuminance [lx], $r$:regression coefficient, $T$:threshold

### C. Issues in Introducing the System in a Large Scale Environment

While the effectiveness of an intelligent lighting system has been demonstrated in an actual office, its verification experiments have been all conducted in a small environment (a single office) and following three issues remain in a large-scale environment. The first issue is that lighting control methods in office buildings differ by vendors. For this reason, it is necessary to consider the optimal configuration of an intelligent lighting system for each vendor in implementing it. The second issue is that due to the configuration of a current intelligent lighting system, a control computer is required for each office in which it is implemented and each vendor. Namely, in a large-scale environment, there are problems with the installation cost, installation area, and operating cost of control computer for an intelligent lighting system. The third issue is that improvement work for enabling the individual control of lightings in each vendor's lighting system by using the control computers of an intelligent lighting system is executed for each vendor. This makes the implementation cost of an intelligent lighting system high. Assuming that the number of an intelligent lighting system to be implemented and its scale are expected to expand, it is necessary to solve these issues.

## III. AN INTELLIGENT LIGHTING SYSTEM USING BACNET

In this section, we describe an intelligent lighting system using BACnet. First, we describe the outline of BACnet. Second, we described the configuration of an intelligent lighting system using BACnet. Finally, we described the advantage of an intelligent lighting system using BACnet.

### A. Outline of BACnet

BACnet is a communication protocol for networks which is equipped in buildings, and it is a standard protocol specified by ASHRAE, ANSI, ISO, etc. Unlike with common communication protocols, BACnet standardizes control devices connected to it as a set of objects. This method ensures interconnectivity between systems, various vendor's system is able to interconnect the systems which are constructed by different vendors. In recent years, BACnet has been used in an increasing number of office buildings to manage and control centrally systems in those buildings as doing so enables streamlined building management.

### B. Outline and Configuration of an Intelligent LIghting System Using BACnet

As noted in Section 2, an intelligent lighting system, as it is has problems in implementing and operating it in a large-scale environment. In order to solve those problems, we propose a new intelligent lighting system using BACnet (hereinafter referred to as "BACnet-type intelligent lighting system").

In recent years, BACnet has been used in an increasing number of office buildings to control lighting in offices centrally. In those buildings, however, individual lighting is not centrally controlled by using BACnet, and lighting in each vendor's system is controlled only by turning them on or off at once. Furthermore, the individual control of lighting in each vendor's system is performed by the method unique to each vendor by using ceiling illuminance sensors or infrared sensors, apart from the central control via BACnet. On the other hand, under the configuration of the new intelligent lighting system proposed by authors, lighting in each vendor's system is individually controlled by the central control computer via BACnet.

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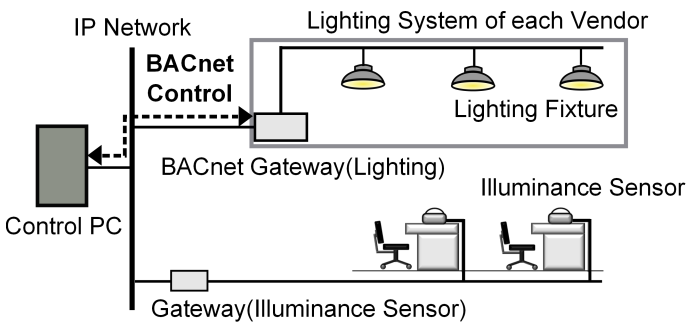


Figure 2. BACnet Type Intelligent Lighting System Configuration

Fig. 2 is the system configuration diagram for the proposed system. The system composed by connecting the control computer of an intelligent lighting system (central control computer) and illuminance sensors to the IP network inside an office building. The control computer controls the lighting individually in each vendor's system in offices on the basis of illuminance values obtained from vendor's systems in offices. As illuminance sensors that can communicate over an IP network are installed, they need not be controlled via BACnet.

### C. Advantages of an Intelligent Lighting System

There are two advantages to the BACnet-type intelligent lighting system. The first one is that it makes the design, implementation, and operation of an intelligent lighting system easy. From the system configuration diagram given in Fig. 2, by using BACnet to construct the system, an intelligent lighting system can be implemented and managed just by connecting the central control computer and illuminance sensors to the IP network in a building. Furthermore, as control is performed from outside vendors' systems using a standard protocol, it does not depend on the lighting control system in each vendor's system. In addition, as centralized control is possible, there is no need to install a control computer in each office, which able to reduce cost.

The second advantage is that the proposed system enables realizing the further optimization of an office space by controlling lighting in coordination with air-conditioning and blind instead of controlling it alone. This is because, as the integrated protocol makes different systems interconnectable with each other, various systems can be controlled in coordination with each other. There are, however, two issues with the BACnet-type intelligent lighting system, which are described in the following section.

## IV. Issues of an Intelligent Lighting System Using BACnet

In this section, we describe the two issues of intelligent lighting system using BACnet.

### A. Limit of the number of possible dimming levels

In controlling a dimmable lighting fixtures, the number of possible dimming levels varies by how lighting is controlled. The lighting control method in an existing intelligent lighting system had 256 dimming levels by 8-bit PWM control or 1000 dimming levels by digital control. On the other hand, lighting control via BACnet has from 0 to 100 dimming levels in accordance with the BACnet protocol. Namely, the

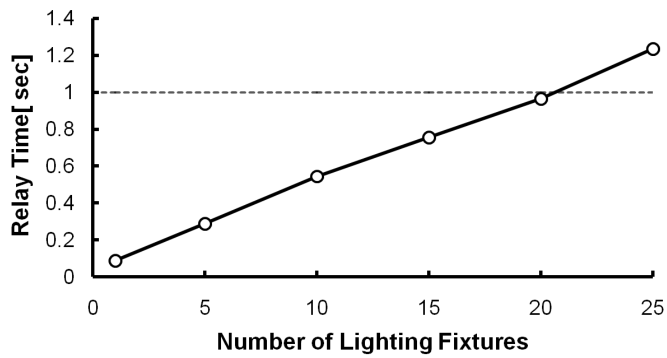


Figure 3. The Time of Sending Control Signal to Starting All Lighting's Luminous Intensity Increase

BACnet-type intelligent lighting system has 100 dimming levels irrespective of the lighting control methods of vendors. For this reason, the BACnet-type intelligent lighting system offers a smaller number of dimming levels compared with an existing intelligent lighting system. This difference in the number of dimming levels, however, only means the difference in luminance between adjacent levels of approximately 6 cd (for existing 256 levels) and approximately 15 cd (for 100 levels under BACnet) even if with a lighting whose maximum luminance is 1,500 cd. In other words, even on a desktop directly under a lighting, the illuminance value corresponding to one level only differs by approximately 2 lx. Therefore, the same control as exercisable by an existing intelligent lighting system (256 levels) is considered to be possible by 100-level lighting control using BACnet. For the operation verification of the BACnet-type intelligent lighting system, which has a smaller number of dimming levels, it is necessary to construct the BACnet-type intelligent lighting system actually, verify its operation, and compare its operation with that of an existing intelligent lighting system. The verification experiment is described in Section 5.

### B. Delay of Lighting Control

As it takes time from transmitting control signals to starting to boost all lightings under lighting control via BACnet, an impact of the delay needs to be examined. AN intelligent lighting system controls lighting at a certain interval (1 or 2 seconds) in consideration of the time required for lighting luminance to stabilize after a sharp change in the lighting environment and a change in lighting luminance. If, however, the lighting control interval becomes longer due to a delay in lighting control, it takes more time for illuminance to converge to the target illuminance. Therefore, it is required to maintain the current lighting control interval (1 or 2 seconds). In consideration of this, the BACnet-type intelligent lighting system sets the lighting control interval to 2 seconds. That is, in order to ensure time for lighting luminance to stabilize (1 second per step), the boosting of all lightings needs to be completed within 1 second. Thus we measured time required to start boosting all lightings by individual lighting control using BACnet. In this measurement, lighting luminance was changed from 40% to 50%.

Fig. 3 shows a graph indicating time from transmitting control signals to lighting fixtures via BACnet to starting to boost all lighting fixtures. The vertical axis denotes time

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required to boost all lighting fixtures and the horizontal axis denotes the number of lighting fixtures controlled. Fig. 3 shows that individual lighting control using BACnet can only control approximately 20 lighting fixtures per second. In other words, in order to maintain the same convergence time to the target illuminance as the existing intelligent lighting system has, the BACnet-type intelligent lighting system is limited to an office with 20 or less lighting fixtures. This delay in control is considered to be caused by the fact that control signals transmitted by the central control computer control lighting fixtures via various equipments including the IP network (media for BACnet communication), BACnet gateways located on each floor or in each office, and lighting control equipments in each vendor's system.

Groups of 20 lighting fixtures individually controlled per second can be controlled in parallel if they are on different floors or in different offices supporting a BACnet gateway. Time required for controlling this number of lighting fixtures is considered to differ somewhat by the performance of the control PC and BACnet supporting equipments. If all lighting fixtures are controlled at the same luminance instead of being individually controlled, as an effective instruction is sent once to all lighting fixtures then, lighting control via BACnet does not take time in controlling. On the other hand, in an office where the number of lighting fixtures is more than 20, the number of lighting fixtures to be controlled simultaneously needs to be 20 or less in order to control them without a delay. This is covered in Section 6.

## V. Verification Experiment of an Intelligent Lighting System Using BACnet

In this section, we build the BACnet type intelligent lighting system and perform an operation experiment. First, we describe the outline and environment of experiment. Second, we describe the result of the experiment.

### A. Outline of Experiment

This section examines the limitation of dimming levels of lighting fixtures mentioned in Section 4.1. This verification experiment verifies the operation of the BACnet-type intelligent lighting system with a smaller number of dimming levels and examines the difference in performance between this type of system and an existing intelligent lighting system. A BACnet-type intelligent lighting system was constructed to perform verification. This experiment used a BACnet-ready transceiver, gateways, and lighting equipment made by Mitsubishi Electric Corporation as a lighting system inside a vendor's system. Fig. 4 shows a part of system constructed. The gateway is connected to IP network (BACnet communication media) and further to the central control computer.

This experiment was conducted in a small room with 20 or less lighting fixtures (the number of lighting fixtures was 9) in order to verify the operation of a BACnet-type intelligent lighting system. That is, the delay time in lighting control via BACnet does not affect the control time of an intelligent lighting system. This experiment was intended to verify that an intelligent lighting system can operate normally by lighting control via BACnet with a smaller number of dimming levels and to compare its operation with that of an existing intelligent lighting system. An experiment was thus conducted on convergence to the target illuminance to

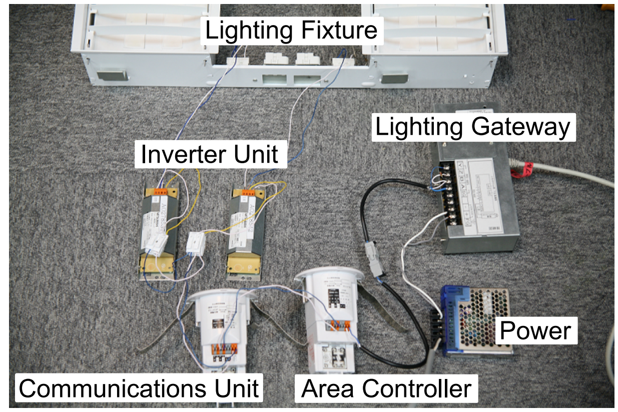


Figure 4. BACnet Corresponding Signal Transceiver of Mitsubishi Electric Corporation

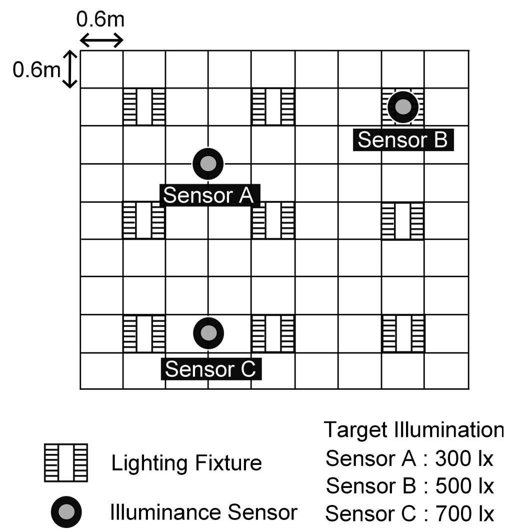


Figure 5. Illuminance Sensor Layout Plan and LED Lighting

verify the operation of the BACnet-type intelligent lighting system and compare the results of control by an existing intelligent lighting system and the BACnet-type intelligent lighting system.

The experimental environment was composed of 9 dimmable LED lighting fixtures and 3 illuminance sensors made by Mitsubishi Electric Corporation. Fig. 5 gives the layout of illuminance sensors relative to LED lighting fixtures and the target illuminance of each illuminance sensor. As shown in Fig. 5, the target illuminance of Illuminance Sensors A, B, and C is, respectively, 300 lx, 500 lx, and700 lx.

### B. Result of Experiment

As stated above, this section shows the result of the target illuminance convergence experiment of the BACnet-type intelligent lighting system and the comparison experiment with an existing intelligent lighting system. First, we indicate the result of the target illuminance convergence experiment.

Fig. 6 shows the result of convergence to the target illuminance by the BACnet-type intelligent lighting system. The horizontal axis denotes the number of steps taken by the BACnet-type intelligent lighting system, and the vertical axis denotes illuminance obtained from illuminance sensors.

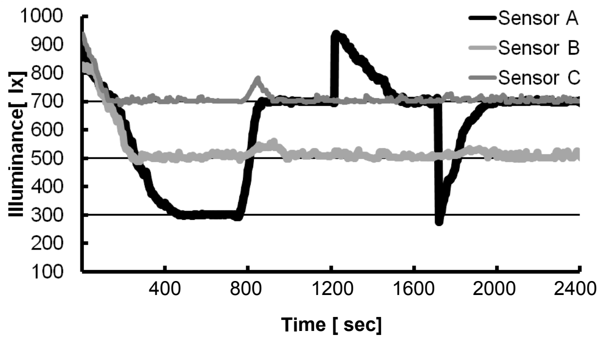


Figure 6. Illumination Convergence of BACnet Type Intelligent Lighting System

As Fig. 6 shows, in approximately 100 steps (approximately 400 seconds) after an intelligent lighting system started up, the illuminance obtained by every illuminance sensors converged to the respective target illuminance.

In this case, approximately 100 steps (approximately 400 seconds) were required to reach convergence. This is because an intelligent lighting system changes the luminance of lighting so slightly as to be not perceived by workers in order not to disturb their work. Furthermore, an intelligent lighting system performs a regression analysis to obtain the positional relationship between lighting fixtures and illuminance sensors during the first 50 steps from its start-up. For this reason, since luminance cannot be efficiently changed during the regression analysis, convergence to the target illuminance takes time. As this regression analysis, however, needs to be performed only at the start-up of the system, convergence to the target illuminance in about 50 steps (approximately 200 seconds) is possible purely in terms of illuminance convergence.

Next, the target illuminance of illuminance sensor A was changed from 300 lx to 700 lx at around 200th step. It is shown that, as a result, the illuminance of the illuminance sensor A converged to 700 lx while the target illuminance of each of other two illuminance sensors was satisfied. It is shown that illuminance convergence in several steps was possible as this was illuminance convergence to greater illuminance and the regression analysis had been completed.

Next, the light of a task light was cast on illuminance sensor A in order to simulate natural light. A sharp rise in the illuminance of illuminance sensor A in approximately 300 steps was due to the light from a task light. As desktops near Illuminance Sensor A became brighter than necessary, an intelligent lighting system lowered the luminance of ceiling lighting fixtures around the illuminance sensor to make illuminance converge to the target illuminance. As a result, illuminance converged to the target illuminance again as shown in Fig. 6. As described above, it was confirmed that an intelligent lighting system was able to operate normally even if lightings were individually controlled by the BACnet-type intelligent lighting system.

Next, in order to verify the performance of the BACnet-type intelligent lighting system, the convergence results of the BACnet-type intelligent lighting system and an existing intelligent lighting system were compared by focusing on illuminance sensor B. Fig 7 shows the graph comparing the histories of target illuminance convergence for both systems. The result of comparison shown in Fig 7 indicates that there

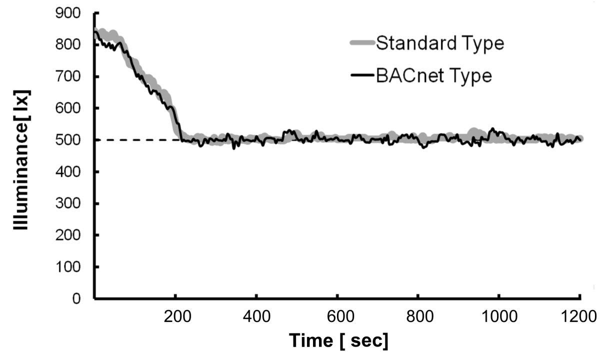


Figure 7. Comparison of Convergence History in The Sensor B

was no difference in the convergence time of illuminance between standard type and BACnet type of an intelligent lighting system. The verification results show that an intelligent lighting system can be normally controlled by individually controlling lighting fixtures via BACnet.

It also turned out that there were hardly any differences between the BACnet-type intelligent lighting system and an existing intelligent lighting system in terms of convergence time and error. It follows from this that the BACnet-type intelligent lighting system can have the same performance as an existing intelligent lighting system and that it is an effective system for making the development, implementation, and operation of an intelligent lighting system easier.

It is, however, necessary to conceive a method to deliver the same performance as an existing intelligent lighting system even if the number of lightings in each office is greater than the number of controllable lightings (20). A method is thus proposed to prioritize lightings in controlling them instead of controlling them in an equal manner. This method is considered to enable controlling the BACnet-type intelligent lighting system without delay in an office in which the number of lighting fixtures is more than 20. This is described in the next section.

## VI. Verification of an Intelligent Lighting System Using BACnet in an Large Scale Environment

In this section, we perform a simulation assuming the large scale office environment to solve the issues shows in Section 4. First, we describe the outline of simulation. Second, we describe the result of simulation.

### A. Outline of Simulation

In this section, we verified using simulation whether an intelligent lighting system to work conventional equivalent without delay in the number of lighting fixtures more than 20 room described in section 4.2. In Fig. 8 shows the simulation environment. The number of dimmable lighting fixtures without delay at the same time in the lighting control using a BACnet is 20 units. Therefore, it is necessary to operate an inttelijent lighting system to control lighting fixtures to below 20 units in an office in which the number of lighting fixtures is more than 20. In this simulation, it compares the realization rate of the target illuminance in a conventional intelligent

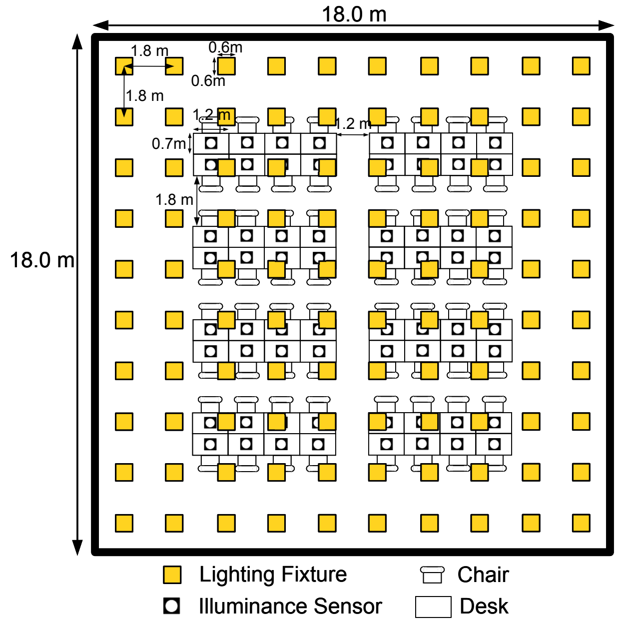


Figure 8. Simulation environment

lighting system without using BACnet (conventional method) and proposed method using BACnet.

Fig 9 shows the simulation environment. Simulation will assume the day from 7:00 to 22:00 and workers come to the office from 7:00 to 8:30 and leave the office from 17: 30 to 22:00 and that number of workers increases and decreases linearly during those periods of time. In addition, workers leave their seat for 1 hour once a day. The target illuminance of each worker is random and ranges from 300 lx to 700 lx.

## B. Result of Simulation

In this section, we verify the realization rate of the target illuminance in the proposed method. Realization rate of the target illuminance shall be realization if the illuminance in the range ± 10 % of the realizable illuminance. Realizable illuminance represents a value that illuminance is converged using the conventional method. This is to verify whether even if the target illuminance can not be achieved by physical factors, there is no difference in illuminance to provide the conventional method.

Fig 9 shows the result of simulation. The average of the illuminance realization rate was 91.5 % in the proposed method. As shown Fig 9, even when using the proposed method, it was possible to realize the illuminance as in the conventional method.

In the control algorithm of an intelligent lighting system, each lighting is linked to extract the illuminance sensor is greatly affected by the luminance changes. The number of lighting each illuminance sensor is linked depend on the location, and the illuminance sensor is linked to the lighting of the 4 or 5 lights. Lighting that is linked to the illuminance sensor is luminance change amount increases when the illuminance sensor is significantly different value as the target illuminance. Therefore, If the illuminance sensor doesn't converge to the target illuminance, the target illuminance is achieved by controlling the lighting of 4 or 5 lights near the illuminance sensor. Thus by preferentially control the lighting

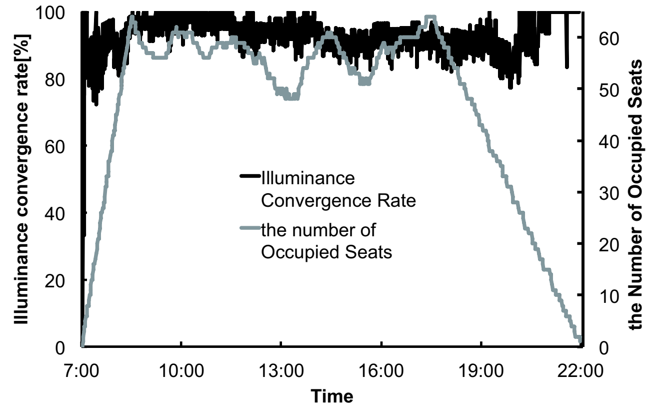


Figure 9. Simulation result

which the luminance changes greately, the proposed method can exhibit conventional method the same performance.

## VII. Conclusion

A current intelligent lighting system has issues in its diffusion to common offices as well as in its implementation and operation in a large-scale environment. In order to solve these issues, we proposed an intelligent lighting system using BACnet. The result of verification experiment showed the BACnet-type intelligent lighting system can have the same performance as an existing intelligent lighting system and that it is an effective system for making the development, implementation, and operation of the Intelligent Lighting System easier.

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