VISUAL COMFORT CONSIDERED LIGHT CONTROL METHODS FOR ENERGY EFFICIENT OFFICE BUILDINGS
A Case Study

by

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This paper presents and investigates the performance of light control methods for energy savings with optimal visual comfort in open-plan office. By grouping personal light zone and tracking user's location, we can provide an energy efficient light control in the office. Simulation and pilot testing results show that more than 60% energy savings could be achieved while providing recommended visual comfort level for each user. Since the proposed methods provide unprecedented energy savings, it can be said that this is a remarkable energy saving technology in the field of light control.

Key words: *light control, energy savings, visual comfort*

Introduction

Artificial light accounts for 40% of the energy usage in office buildings and often constitutes the largest proportion of energy consumption among all electrical systems [1]. Hence, it is very important to save light energy by efficient systems and control methods.

Most of the present buildings still adopt a legacy light control policy. For example, administrator usually binds a group of lights with a control switch or motion (occupancy) sensor for each space in a building. It can be efficient for a closed area like rest room or meeting room. Similarly, in an open-plan office, lights are usually selected in a straight line and mapped with a wall switch to be controlled by users. However, in this case, such control is not efficient as multiple users work and move individually. For instance, consider the case when only one user is working overtime in the office and wants to have minimum required illuminance over the workspace. The user needs to turn On the switch mapped to 10 lights, even though only 3 lights are enough for the required illuminance.

We propose an algorithm adopting a visual comfort optimizing energy-efficient light control method that minimizes energy consumption by allocating selected lights, while ensuring personalized visual comfort for each user in an open-plan office.

Researchers have been quantifying energy savings from light controls in commercial buildings for more than 20 years. Generally, there are two prominent ways to reduce light energy consumption. One class of methods focuses on installation of enhanced instruments and new systems for lighting. For example, an LED is an energy efficient device for emitting light, which consumes about 50% less power than a fluorescent lamp. The second class examines optimal light control techniques.

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An on/off control strategy based on occupancy sensors can save 35% energy in an office set-up [2]. A dimming control technology utilizing daylight or blind control is another popular approach to reduce light energy consumption considerably. A genetic algorithm for the control of dimmable lighting is introduced in [3]. Daylight harvesting is the most energy-efficient control strategy for offices in perimeter zones where significant daylight is available [4]. Light level tuning technique which reduces light level according to occupants' lighting preferences is particularly effective in private offices but not in open-plan offices since no single light level will satisfy all individuals' needs [5]. A research shows that allowing occupants to work under their preferred lighting may not only increase productivity but can also be energy efficient [6].

Based on a review of 240 energy savings estimates published in 88 papers and case studies, it is known that 38% of energy savings can be achieved through various combinations of light control technologies based on occupancy control, daylight harvesting, and dimming [7]. An iterative optimization framework was examined in [8] with objective of reducing power consumption while achieving illumination constraints at light sensors, spatial dimming uniformity requirement, and physical limits on dimming levels. In [9], daylight harvesting, occupancy control, and light level tuning strategies are formulated into an optimization problem that generates light outputs for each luminaire to produce the desired lighting at each workstation with minimal energy usage.

Workstation-specific lighting has the potential to achieve large amount of energy savings in an open-plan office without reducing the quality of workspace illuminance conditions. [10] illustrated such a workstation-specific system that achieves 40% energy savings compared to an uncontrolled retrofit alternative while providing higher desktop light levels and improving occupant satisfaction. In [11-14], optimization was done based on feedback of light sensor measurements at the workspace plane, sensors being carried by users or placed at desks.

Some research shows an effect of architectural design exploiting natural light, building materials, and arrangement of lights on energy savings [15-17].

Proposed algorithms

We propose light control algorithms suitable for open-plan offices where multiple users coexist. If an aggregated illuminance arriving to the user's eyes is not below a required level, we assume the visual comfort is satisfied, similar to existing work [18]. It is essential that the visual comfort is not compromised for even a single user. Along with maintaining the minimum required illuminance, an algorithm should not make frequent light level changes, as it can violate a user's visual comfort as well. Therefore, we also suggest a light level change technique to minimize the negative affect of this phenomenon.

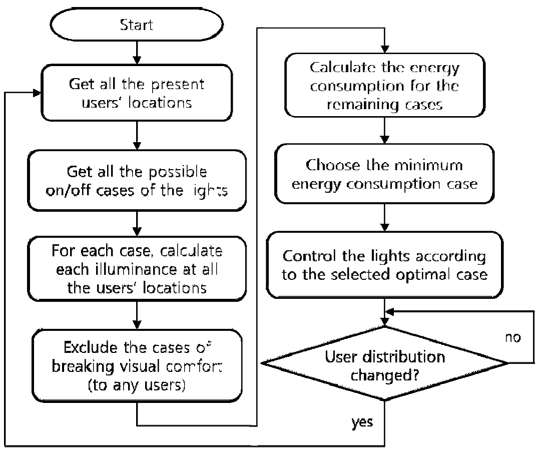

Figure 1. An optimal light control method

Optimal light control

The optimal light control method in the viewpoint of energy consumption is shown in fig. 1. This algorithm comprises only of *On* and *Off* control, and not dimming control. By using IPS (indoor positioning system), we can get the locations of the users who are currently present at their workspace, under a given user distribution. Then we obtain all the possible scenarios consisting of each light's on/off status. For a system with N lights, there will be 2^N cases. For each case, the illuminance at each user's location is calculated. Daylight can be included by adding the current external illuminance. Next, the cases where the condition of minimum required illuminance is not satisfied, are excluded from the analysis, and calculate energy consumption is calculated for each of the remaining cases. The minimum energy consumption case is chosen, which will be the optimal light control distribution at that specific time. When a user moves in the office, the user distribution changes, and the process must be repeated to adapt to the changed situation.

Although the algorithm reveals the optimal light control, high computational complexity makes it difficult to implement. Additionally, if users frequently move in the office, a blinking phenomenon would occur consequently, annoying user's visual comfort. Therefore, we propose a more practical algorithm next.

Zone-based control

A zone-based control algorithm determines a light zone (called *myZone*; shortly, zone), which contains lights providing minimum required illuminance to a user's workspace, *e. g.* around work desk. The lights in the zone are automatically switched on and off together depending on the user's presence at the workspace, in order to achieve maximum energy savings.

Figure 2 illustrates an example of a zone in a mobile application. If a user designates his workspace on the UI (red dot), a zone for the workspace is assigned to the user. For simplicity, only the light layout is illustrated in fig. 2. However, in a real setting, the office layout is overlapped with the light layout to help a user easily point out their workspace. It can be seen from the figure that 6 lights are allocated to the user.

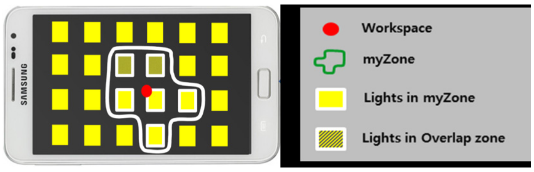

Figure 2. An example of *myZone* and overlap zone illustration (*for color image see journal web site*)

Figure 3 shows a flow diagram of the proposed algorithm. Assume that all lights are turned off at the initial state for each user.

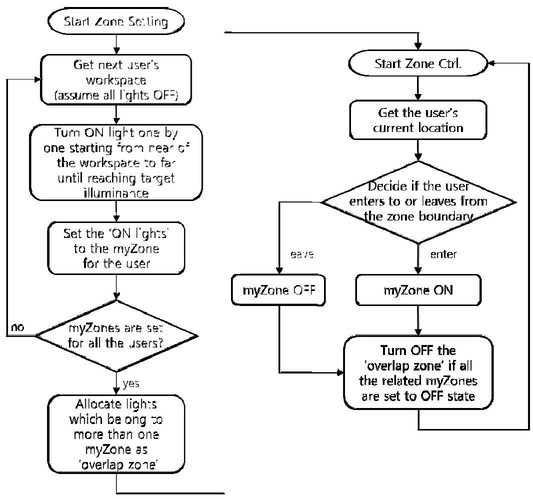

Figure 3. An example of *myZone* and overlap zone illustration

Zone selection

Left side of fig. 3 depicts how to select the lights and allocate them to a user. *myZone*, a dedicated zone for every user, contains minimum number of lights guaranteeing visual comfort to the user's workspace. The illuminance E at a point on a surface is given by the formula:

$$E = I / d^2 \tag{1}$$

where I is the luminous intensity of the light source in candelas and d – is the distance in meters. We can observe that, the closest light to the user contributes the highest illuminance to them.

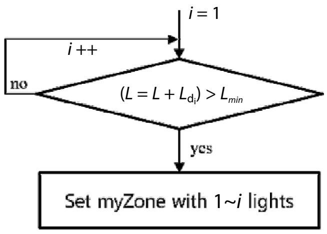

Figure 4. Programming logic for light selection

This gives us an important insight about how to allocate the lights to a zone. The scheme for selecting lights is presented in fig. 4. The total illuminance L can be measured by a light sensor or calculated by a dedicated software implementing radiant environment based on complex optical formulas.

Here, d_i is the light index of the i_{th} closest light to the workspace. The index is sorted in ascending order according to the distance of the light from the workspace. After the user's workspace is designated, the nearest Off light is turned On and added to the user's *myZone*. This process is repeated until the accumulated illuminance measured in the workspace exceeds L_{min}, the minimum required illuminance level for visual comfort. After that, the light index from 1 to i is allocated to the user's *myZone*. Note that, L_{min} can be determined by predetermined standards or each user's preference. For example, EN12464-1 standard specifies that the minimum required illuminance level in task area should be greater than or equal to 500 lux.

Daylight can be incorporated into the algorithm while calculating the illuminance. We can use $L_{min} - L_{dl}$ instead of L_{min} , where L_{dl} is the external illuminance contributed by the daylight. In this case, a periodic re-calculation is needed to determine the zone since the daylight changes with time.

In fig. 2, the two lights that belong to multiple *myZones* are classified into overlap zone (diagonally striped squares). To ensure the visual comfort, lights in an overlap zone *i. e.*, overlapped lights (or shared lights) should be turned On, when at least one of the zones, where the overlapped lights belong, is turned On. Therefore, the overlap zone should be turned off only when all the zones containing any of the overlapped lights are turned off.

Zone control

The right side of fig. 2 shows occupancy based light control. Here we introduce a term: zone boundary, as a physical boundary to decide whether a user enters into or leaves from the zone. It is defined as a circle centered at the user's workspace. Default radius of the zone boundary is 5 m, which can be modified according to the accuracy of IPS which determines the user's location.

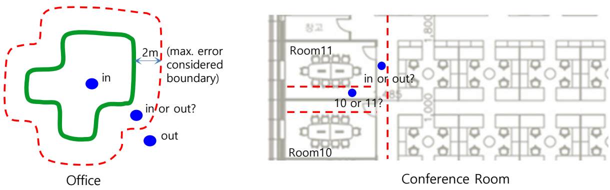

Figure 5. Consideration of IPS error in the localized control

When a user enters into his zone boundary, the system turns On the lights in the zone. On the other hand, if the user gets out of the zone boundary, the system will turn Off the lights in the zone. To prevent frequent flickering of lights, a buffer On time of 10 minutes is kept before the zone is switched off, so as to make sure that the user is away from the workspace. Of course, if the user wants to control the lights manually, they can do it via a mobile application at any time. While determining whether a user is in or out of a zone boundary, we must consider an inevitable error induced by IPS. Figure 5 presents a case where the maximum error distance is 2 meters. What if the user's position is inside the error boundary? (within the dotted line in the picture.) In the office, to secure the visual comfort thoroughly, we assume the user to be inside the zone boundary. In case of error boundary across a conference room, however, the user should confirm the exact location manually via mobile application, since it is difficult to decide the exact conference room number due to the IPS error. (especially, in case of cascading conference rooms).

Dimming control

We define a total illuminance L for user i as:

$$L_i = \sum_j E\left(l_{ij}\right) + D_i + A_i \tag{2}$$

where l_{ij} is the index of j^{th} nearest light from user i and $E(l_{ij})$ is the illuminance for user i due to the light l_{ij} which can be calculated by (1). D_i is the illuminance affected by daylight and A_i is the ambient illuminance to user i generated by the other lights except the user i's *myZone*, computed as an aggregation of l_{ij} (note that A_i was 0 in the previous algorithm). Now, we introduce another algorithm which considers the ambient illuminance and dimming control technique in fig. 6.

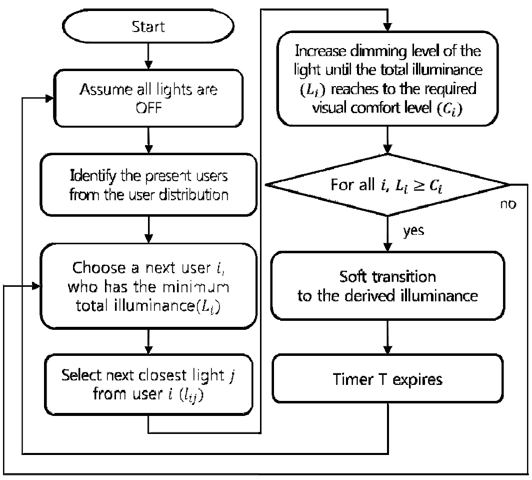

Figure 6. A dimming light control algorithm

First, assuming all the lights are off, determine which users are present and their locations. Among the present people, choose a user who has the lowest illuminance at their location. Initially, a random person i will be chosen since there is no illuminance. Select the j^{th} closest light from user its workspace. Increase the dimming level of the light l_{ij} until L_i reaches C_i, the minimum illuminance criteria set by user i. (If dimming is not allowed, you can set the level to 0 or 100%, in other words, only on or off status is possible. Note that the power consumption of a luminaire is proportional to the actual light output [19].)

This process is repeated until the illuminances for all the present users are greater than or equal to the minimum required illuminance, here 500 lux. Next, the dimming levels of the lights are changed from the previous dimming status to the newly derived dimming values. Note that, actually the light level control action is performed at this step. (Before this step, we just derived the proper illuminances of the lights internally.)

Here, we gradually change the brightness, through so-called *soft transition*. For example, if 30 seconds are given for the soft transition and a light's dimming level has to be changed from 10-70%, then the dimming level will be increased by 2% every second. By doing this, we can protect the user's visual comfort from any abrupt brightness alteration.

After the soft transition, wait T seconds. Although the soft transition alleviates the visual discomfort, if we apply new illuminances to the lights whenever the user distribution is changed, it would be still a potential problem. Therefore, we set a timer to add some waiting time. The amount of the time depends on how frequently the users move. If the users don't move actively, we can set the timer longer in order to keep the visual comfort for as long as possible.

Simulation

The *myZone* based light control algorithm is the most practical algorithm from the viewpoint of implementation and usability. We construct a simulation environment and analyze

Parameters	Description
Dimensions	21 m × 16 m × 2.8 m
Occupant	63
Light	Equally-spaced 63 lights (60 cm × 60 cm Maltani Glide 600T)
Etc.	Exclude daylight effect

(a)

Time	Polley
06:00	Turn on 1/3 of the lights
06:30	Turn on all of the lights
12:00	Turn on all of the lights
13:00	Turn on all of the lights
21:00	Turn on 1/3 of the lights
24:00	Turn on all of the lights

(b)

Figure 7. (a) Simulation environment and parameters, (b) light control policy in Umyeon campus

its performance. The algorithm is evaluated in an open-plan office environment. We use Radiance, a well known software for radiant ray simulation. The office room model in Radiance is a single large room with total area of 3600 ft^2 and 63 (9×7 array) lights are installed. Main parameters are presented in fig. 7(a). The 63 occupants' movements are modeled with their real occupancy pattern estimated from the windows' log in and log out time. We referred to a regular office in Samsung Umyeon campus to decide the spacing of lights and the density of occupants in the simulation. Figure 7(b) reveals the light control policy of the campus. We do not consider daylight in the simulation. (L_{dl} = 0).

Radiance

Radiance is a tool used for computing illuminance at a specific point in the simulated environment. Inputs to the tool include the information about objects in the office, their material properties and light sources. The geometry is usually modeled with a CAD program (Sketchup in our case) and exported to the Radiance input file (*.rad). It has the information about shape, size and position of all the objects in the space. Material properties must include the type of the material (plastic, light, mirror, metal, *etc*.), texture or pattern applied to the material (if any) and parameters that define the material (RGB reflectance, specular reflectance, roughness, *etc*.).

Light sources include the luminaires, sun, windows, *etc*. Most of the major luminaire manufacturers provide *.ies files which define the illuminance distribution curves of their luminaires. The luminaire used in our simulation is Maltani's Glide 600T LED module with luminous flux 4000 lumen. Figure 8(a) shows the illuminance distribution curve of the luminaire. The sky model used is the CIE standard sky distribution at noon on April 28, 2016 at Seoul (37° 34′ N 126° 58′ E).

To validate the feasibility of the tool, the illuminance values at some points are compared. Assume just one light is switched on in a dark room. Figure 8(b) represents two illuminance distribution curves measured by a lux meter, and calculated by Radiance at randomly selected points. The difference between the Radiance calculated value and real measured value is only about 30 lux (at 2.5 m from the center of the light source). The difference comes from the inaccurate modeling of the environment, because the furniture, fixtures and objects, which can affect the reflection and absorption of the lights inside the room, couldn't have been modeled perfectly in the Radiance.

The above result suggests that Radiance, when modeled and calibrated carefully, can be used to get the illuminance values at the points of interest, instead of using expensive light sensors that need to be installed at every workspace in the office.

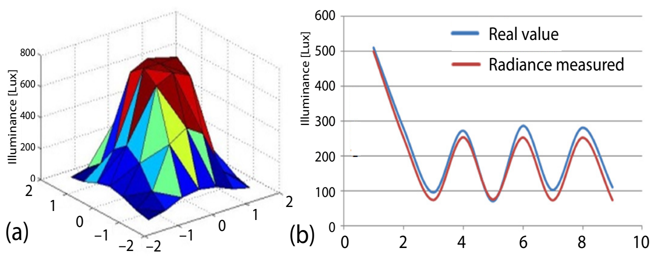

Figure 8. (a) An illuminance distribution of luminaire Glide 600T modeled by *.ies file, (b) comparision of illuminances calculated by Radiance and measured by a lux meter

User occupancy patterns

Building energy simulation programs like EnergyPlus usually employ average occupancy ratio (ratio of occupied time duration to the sum of occupied and unoccupied time durations) to compute the energy consumption of source devices operating based on occupancy. Since the proposed algorithm introduces the concepts of buffer time and overlap zone, simple average occupancy ratio is not enough for accurate simulation. This poses a challenge, in terms of unavailability of public data of user occupancy as well as indoor location data, because IPS is not a common trend used in office environments yet. To overcome this challenge, we designed an application that keeps track of timestamps of Windows login and logout time of each user. The assumption in this approach is that a user is at their workspace when the user is logged in to the PC, and out of the workspace when logged out, possibly due to meetings, lunch or coffee break. The application was distributed to 9 colleagues and their log data was collected over 2 weeks. The data is used 7 times to generate occupancy patterns for 63 people.

The average working time (last logout – first login) is 10 hours and 18 minutes, as observed from the collected occupancy data. The average time spent at the workspace is 6 hours and 18 minutes (61% of working time), which means about 39% of the total time spent in the office is not counted at the workspace, but at the conference room, lounge, rest room or outside.

Pre-calculation of myZone

Radiance employs a backward ray-tracing algorithm. It means the light rays are traced back from the point of measurement to the source. To get a *myZone*, the ray-tracing computations are required every time a user's request arises. Since the computation of ray-tracing is time consuming, it is hard to implement in real-time. Therefore, we pre-computed the zones at selected points of the room and used this data to allocate a zone for each user in real-time. For the purpose, we divided the entire space into a fine grid (0.5 m × 0.5 m) and made a database of zones at each grid point. Each user's location is rounded up to the closest grid point to get the *myZone* from the database immediately. The grid distance is designed fine enough to ensure that the zone calculated at the user's real workspace is quite similar to the pre-computed zone at the corresponding grid point.

Results and observations

To verify the energy savings, several scenarios are prepared as shown in fig. 9(a). The baseline is considered to be the case that the light energy is maximally consumed in the office which means all the lights are turned On throughout the day (blue). If we compare the difference of energy consumption between the baseline and the case where the proposed algorithm is applied for 24 hours (red), we can observe 63% energy savings. The energy savings seem so high because the baseline is 24 hours on.

In Samsung Umyeon campus, the light on/off schedule is determined by a policy as shown in fig. 7(b). In Figure 9(a), this policy (green) shows 61% energy consumption, as compared to the baseline. If we compare this with *myZone* 24 hours case, we get 39.3% savings.

Figure 9(a) also shows that if we apply the algorithm for all the time except 9:00 a. m. to 6:00 p. m. (working hours), we can achieve 48% savings. The other scenario is to apply the algorithm only in the light off time (before 8:00 am, after 8:00 pm and lunch time), and energy savings of about 43% are reported for this case.

Increasing the number of lights from 63 to 108, we can save 24% additional energy. If the lights are deployed in higher density, a smaller number of lights can be allocated to each zone. It can increase the number of turned-off lights and therefore, reduces the energy con-

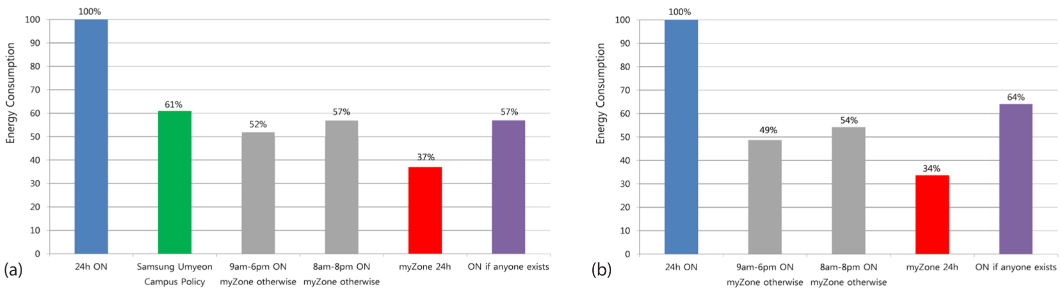

Figure 9. Simulation result for each scenario (a) Samsung Umyeon campus, (b) Spire tower
(*for color image see journal web site*)

sumption. Following the same reasoning, a similar result can be obtained when we decrease the height of the office room.

Spire tower simulation

We have also simulated the algorithm at 22nd floor of Spire tower in Poland. Spire tower is a 48 storey-office building, and its 22nd floor contains about 200 lights, as illustrated in fig. 10. There is no light control policy in Spire tower. Users can turn on or off any lights by controlling the light control switches attached on the wall. All the other parameters and conditions are same as the previous case.

As shown in fig. 9(b), the results are similar to fig. 9(a). When we apply the algorithm for 24 hours, 66% of energy savings can be achieved in comparison with the baseline. Because we used the same occupancy patterns as before, similar results could be obtained. We conclude that the proposed algorithm can save more than 60% energy, while keeping the visual comfort for all the users in an open-plan office.

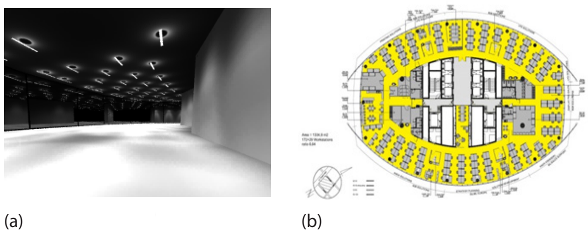

Figure 10. (a) Geometry and light modeling in Radiance, (b) layout at 22nd floor of Spire tower

Pilot test

We implemented a software suite including a mobile application for user, web portal for administrator and server system for the algorithm as shown in fig. 11. We used a 3rd party light control system, Helvar. Helvar's light control router communicates with our server system via their proprietary protocol, HelvarNet. We installed the system at 22nd floor of Spire tower to test the feasibility and performance in the real environment.

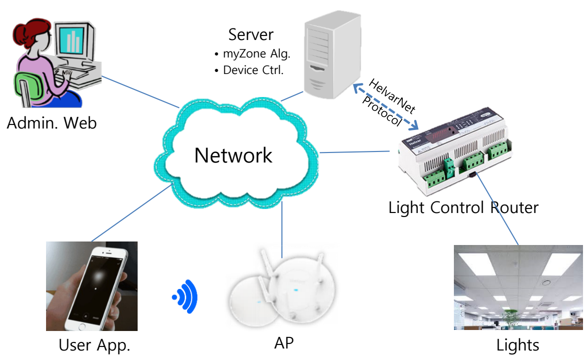

Figure 11. Light control system architecture for the Spire tower pilot testing

The application was rolled out to 120 people. It is important to identify the number of people who use the application. For example, 50% participation of users is different from the case of 70% participation, in terms of performance verification. The participation ratio can be estimated from a user survey or IPS data analysis. It turns out about 70% of people used the application during the test period. When determining the zone, we do not consider the illuminance of those lights, which are not included in the corresponding user's zone (= 0), as well as the daylight from windows.

To avoid the customer complaint, we allow for users to control the dimming level of their zone using a control bar in the application. Shared lights are set to the highest brightness value among the values set by the shared users in order to secure the minimum required illuminance.

Figure 12 shows the energy consumption at 22nd floor of Spire tower in response to different light control policies. For winter period, we collected the data for 3 weeks from October 17th to November 4th 2016. The daytime is roughly from 8:00 a. m. to 3:30 p. m. in this period. In the policy *myZone*(P1), all the light control switches are disabled, meaning that the user should install and use the application in order to turn on or off the lights. Whereas, *myZone* (P2) enables the switch control while using the application. Note that the user control policy is the default policy in Spire tower. It allows for users to control any lights via the physical light control switches on the wall whenever they want. With P2 policy, we can see 43% savings can be achieved in comparison to the default policy, while 51% savings can be achieved in P1. Energy consumption can be reduced further if we disable the light control switches and force the use of app.

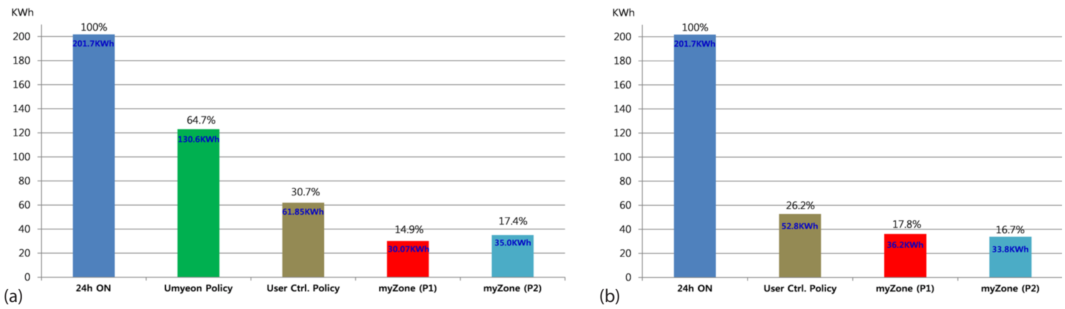

Figure 12. Real energy consumption in 22nd floor at Spire tower; (a) winter, (b) summer

For summer period, we collected the data for 4 weeks from April 17th to May 12th 2017. Since the Sun is in the sky roughly from 5:30 a. m. to 8:00 p. m. in this season, we expect the energy saving performance of the algorithm to degrade. Due to the long sunshine duration, people tend not to turn on the lights, owing to enough daylight. As you can see in fig. 12(b), the energy consumption of the default policy is lower than the case of winter, meaning the denominator of the energy saving ratio will be decreased. Therefore, the energy savings are only 32% and 36% for P1 and P2 policies, respectively. Here we can see the performance in P2 policy is lower than P1. The reason is that most of the people do not usually turn on the

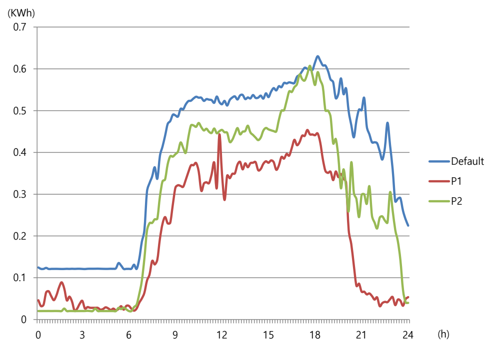

Figure 13. Average daily energy consumption in 22nd floor at Spire tower

wall switch, even when we allowed them to do it, due to ample daylight. As a result, allowing switch control becomes meaningless in summer.

Figure 13 shows the daily average energy consumption trend in winter. People start to come to work from 6:00 a. m. to 10:00 p. m. Around 5:00 a. m., after the sunset, energy consumption reaches its peak value. After 6:00 p. m., most of the people start to get off work. We can use this information, together with other appliances' energy usage pattern, for an energy efficient demand-response scheduling [20].

Conclusions

We conducted a short poll to see the the statistics of overall user satisfaction. 67 people out of a total of 120 responded to the survey. For the question *Would you like to use the application every day at work?*, 51% of people said *yes* and 24% said yes, but with switches whereas 25% said *No*. Among the users who said *No*, 59% gave reasons relating to poor quality of the app, such as battery overuse, freeze, control delay, inconvenient UI/UX, and so on. Since the app was developed for the purpose of pilot test, we expect the user satisfaction to improve when the application is upgraded.

In this paper, we investigated the algorithm that ensures personal visual comfort in an open-plan office. Simulation and pilot testing results show that more than 60% energy savings could be achieved while providing minimum required illuminance for every single user's visual comfort.

Since the zone based algorithm contributes significantly to energy savings, we can say that it is an energy efficient algorithm for green IoT buildings in visual comfort constrained environments. This algorithm is suitable to be employed to real environment because it is practical, easy to use and intuitive for user.

In another algorithm, we also employed dimming technique and ambient illuminances. However, deploying them simultaneously made the algorithm difficult to implement in practical scenario. It is also hard to analyze its performance quantitatively, because the change frequency and pattern of the user distribution affects the dimming level, soft transition time and timer value. Enhancing the algorithms and analyzing their performances are open to other researchers.

Nomenclature

A_i – ambient illuminance to user, [lx]
C_i – illuminance criteria set by user, [lx]
D_i – illuminance caused by daylight to user, [lx]
d – distance in meters, [m]
d_i – light index of i_{th} closest light, [–]
E – illuminance at a point, [lx]
$E(l_{ij})$ – illuminance caused by light to user, [lx]
I – luminous intensity, [cd]
L – total illuminance, [lx]
L_{min} – the min. required illuminance, [lx]
L_{dl} – external illuminance by daylight, [lx]
l_{ij} – j_{th} minimum distant light from user, [–]

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