

Occupant-Centred Lighting (OCL) to well-being: a review

Iluminatul centrat pe ocupant (OCL) pentru bunăstare: o revizuire

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Abstract. *People in the past spent most of their time outdoors and received the benefits of exposure to natural light. Nowadays we spend a large part of our day indoors where we predominantly use artificial lighting. Against the backdrop of the accelerating climate change we are experiencing, the need to reduce energy consumption in the lighting component of buildings can be achieved by maximising the use of natural daylight during the day in conjunction with identifying the human presence in indoor spaces for efficiency. Occupant Lighting Control technologies offer a real tool to achieve these goals. Adaptive lighting automation controllers, sensor networks and wireless actuators for occupancy-based lighting control, user-centric lighting control based on video cameras, platforms for intelligent lighting control based on life logs are just some of the techniques and methods used to apply Occupant Lighting Control principles. Although lowering energy consumption in buildings is the primary goal of lighting management systems, taking into account the inhabitants' feeling of comfort and their general level of wellbeing is just as vital, if not more so. The adoption of integrative lighting, by complementing natural light with artificial lighting in an articulated manner and in conjunction with the human presence in interior spaces, is the efficient and human-accepted path to sustainable energy efficiency. A collective effort by society is needed to make human-centred lighting an everyday reality.*

Key words. Lightning, services, natural light

1. Introduction

Earth's natural day-night cycle has had a defining influence on human biological and social evolution. Light has been a fundamental factor in human activities, and its changes over a 24-hour period in light intensity and color temperature at different times of the day starting from low values in the morning, peaking in the middle of the

day and then falling to a very low level at night has defined the circadian rhythm for humans.

In the past, 90% of our time was spent outdoors. Humans were immersed in natural light radiation streams, receiving through their sense organs all these changes, and reacting accordingly to these external stimuli. In modern times we spend 10% of our active time in the outside environment, exposed to natural environmental factors. Most of the time we use artificial lighting, present in residential, office, commercial and factory buildings as well as on the streets. The quantitative (illuminance level and luminous flux distribution) and qualitative (luminaire distribution, light color, color rendering, etc.) aspects of lighting can influence the condition of lighting system users, both for better and for worse. In a positive sense, the effects can be increased attention and concentration, increased productivity, physiological and psychological comfort, relaxation, and efficient recovery, etc. In a negative sense, it can lead to disruption of the circadian rhythm and the appearance of health problems, affecting the general state of well-being.

Humankind is facing an accelerating phenomenon of climate change [1]. Against this backdrop of instability, the energy consumption of buildings is increasing. Buildings consume about 30% of the electricity produced worldwide. A review of design thinking for building installations using advanced technologies and renewable energy is needed. The Near Zero Energy Building (NZEB) concept is important to consider, and to apply on a large scale [9].

Building technologies have evolved and buildings with good thermal envelope insulation are now being built. We can even say that they are energy efficient in this respect.

But lighting technologies, although they have moved to LED lighting sources in most buildings, have not evolved that much. There is a phenomenon of increasing electricity consumption generated by lighting systems, due to the level of demand for comfort in indoor spaces, the extended time people spend in buildings, especially late at night, and the lack of an articulated automation system that reduces the level of artificial lighting in proportion to the natural light input, correlates the shading system with the artificial lighting and switches off the lights when people leave the spaces, all done in an efficient but user interactive way.

The concepts of well-being and human centered lighting coordinate aspects of human perception and perception of an interior space and beyond. But the concept that coordinates energy efficiency, and how to achieve comfort while keeping energy consumption at the right level, is Occupant Centric Control (OCC). For lighting, the subject of this article, the concept is Occupant-Centered Lighting (OCL). By implementing in buildings automation systems that employ occupant centered lighting techniques for the actuation and control of lighting systems, optimal energy consumption is ensured while preserving for the occupants the characteristics of human lighting but very importantly also the state of well-being.

A person's well-being is not a concept defined in scientific terms. Even so, there are some parameters that can be considered with serious arguments in influencing the general state of a person in a building (lighting, room temperature, humidity, solar

radiation, brightness (glare), air currents speed, thermal radiation of objects in the room, etc.).

It is universally true that the weighting of one at the expense of another can produce imbalances, and a saving made in one-part leads to cost increases in another. A classic example is that of increasing the glazed area of a facade, which favors access to natural light and leads to lower energy consumption with artificial lighting, but which leads to higher heat input and therefore higher heating and cooling costs for the interior space in question.

A balance is needed, and this involves a fine balancing of energy parameters to achieve a situation that, in the best assessments, can induce a state of comfort and therefore a state of "well-being".

2. Lighting in buildings - economy versus well-being

Building-related activities considerably increase the world's energy usage. 25% of the energy used in commercial buildings in the US is ascribed to lighting, while 12% is allocated to the residential sector. In the EU, lighting accounts for 14% of all energy usage in commercial buildings and 11% in residential ones. To achieve energy-efficient energy consumption, automated lighting control systems are therefore required [10]. Numerous innovations in technology over the years have been successful in lowering the amount of energy used by lighting systems. For instance, traditional passive infrared occupancy sensors have been utilized in structures for more than 20 years. According to numerous studies, these sensors, used to turn on lights when a room is occupied and turn them off after a predetermined amount of time, defined duration of non-occupancy, or time delay, can save up to 38% more energy than human operation [2].

However, there are some drawbacks to control via conventional passive sensor monitoring of occupant presence:

On the one hand, false positive detection may result in the use of illumination that is not necessary. On the other hand, false-negative detection might result in unintended light switching off, such as when a person sits motionless for a lengthy time using a computer. This frequently makes the residents angry.

A system that exclusively employs occupancy sensors does not take the environment into account. Regardless of whether there is any natural light present in the space, the lights will be turned on to their highest setting if a human is identified.

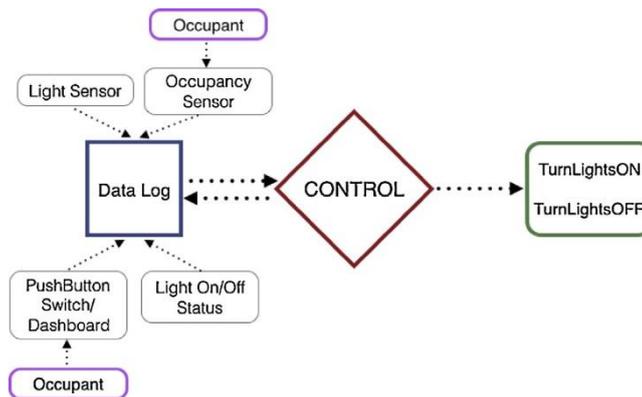


Figure 1. Lighting control system with a focus on the user. [2]

Improved automation system design has been a focus of research and development as of late. Because of this, cutting-edge automatic control methods have been offered, which may not only save more energy but also modify their operations in response to the preferences of the building's occupants.

Research shows that people don't generally prioritize energy efficiency when making home adjustments; rather, they prioritize the comfort of themselves and their guests.

It is necessary to integrate intelligent lighting automation systems in buildings that take into account inhabitants' impression of comfort and well-being, even if the primary goal of lighting control systems is to reduce energy consumption. There is a pressing demand for implementations that can adapt to their surroundings and improve over time.

How well these systems function in terms of energy efficiency and how well they are received by their intended occupants depends on this.

3. User-centred lighting control (OCL): approaches

A comfortable working atmosphere while consuming the least amount of energy are the goals of the current generation of intelligent lighting control systems. Better human-room interaction requires an occupant-centered design approach (a person in a space in a room) [5]. Given the following goals of an intelligent building automation system, occupant context-based lighting control design is required:

- locate a person and, while turning off the lights in empty spaces, change the lighting control to suit the space they are using.
- comprehend the activity of individuals around them to give suitable illumination conditions for various situations and activities.
- integrating lighting and shade technologies to maximize natural light while preserving the indoor climate.

The automation system can be configured to reflect the user's preferences for lighting. For instance, varying light levels and color temperatures can be used to generate various moods based on the time of day or during particular activities (watching films, eating, studying, etc.).

There are algorithms for smart buildings that manage lighting based on the needs of the occupants. A lighting control algorithm based on observations of a network of

sensors situated in one or more rooms is taken into consideration to give suitable lighting settings for various conditions. The system may modify lighting settings to provide an environment that is comfortable for the user while also saving energy by dimming or reducing the light output for particular luminaires after learning a person's position and activities.

3.1. *LightLearn: An adaptive occupant-centred controller*

Because they concentrate only on energy consumption rather than occupant comfort, lighting controllers that incorporate occupancy and brightness sensors to increase energy efficiency are frequently useless. The perfect controller will adjust to the preferences of the users and the surrounding environment.

In their research, Nagy et al. [3] used LightLearn, an occupant-centered controller (OCC) for learning-based lighting.

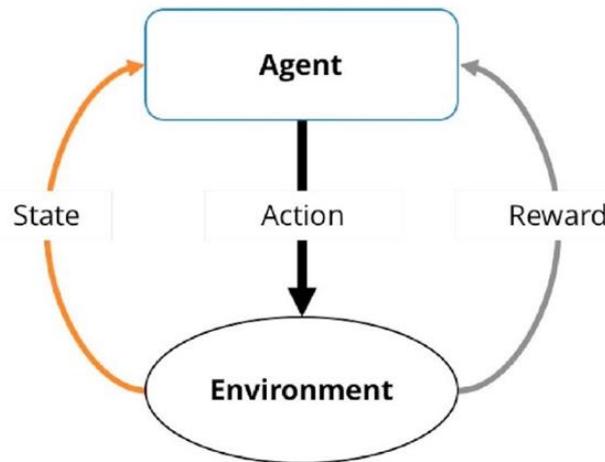


Figure 2. To choose the best course of action, the control agent engages with the environment [3].

It keeps an eye on the amount of both natural and artificial light present in the space as well as how the tenant and the lighting system interact. The best actions for the controller are then decided upon using this data.

LightLearn successfully strikes a balance between consumer energy use and occupant comfort. LightLearn's adaptive features imply that occupant-centered control-based learning is a workable strategy to reduce the disparity between occupant comfort and energy usage.

The Light Utilization Ratio (LUR), which was developed to normalize energy consumption depending on human presence, was one of the initial two metrics employed in the study.

$$\text{LUR} = \frac{\text{time with lights on}}{\text{occupied time}}$$

- The UNC Ratio for Evaluating Human Comfort. This parameter was employed by Nagy et al. [2] to assess the efficacy of their OCC lighting controller by determining how long occupants were subjected to an unsuitable lighting environment before reporting discomfort.

Comfort-to-light levels Sunlight utilization (as measured by LUR) and human comfort (as measured by UNC) are both indicators. The two metrics are not sufficient for evaluating OCC performance, however, for two main reasons: - neither indicator takes into account the connection between occupants, occupant behavior, and energy use. There is also the energy used implicitly by the controller to maintain a pleasant environment and turn off lights when not needed or when the room is deserted if there is ample natural light. However, LUR and UNC have limitations in these types of scenarios.

- Given that LUR and UNC were originally conceived as design criteria, it is possible that they are not well suited for assessing controller performance in the field.

To evaluate the effectiveness of occupant-focused lighting management systems, we propose the Light Comfort-Ratio (LCR) to combat this problem.

Table 1.

LCR performance scores [3].

Controller performance scores in LCR.	
Goal	Score
Occupant is comfortable with lights off	1.0
Occupant is comfortable with necessary energy consumption	1.0
Occupant is comfortable with unnecessary energy consumption	0.5
Occupant is uncomfortable	0.0
Space is vacant with lights off	1.0
Space is vacant with lights on	0.0

To put it simply, the goal is to assign a value between 0 (worst) and 1 (best) to each time step t when the controller is in effect (best). As can be seen in Table 1, LightLearn assigns a value of 0 to occupant discomfort and energy waste and a value of 1 to occupant comfort and mandatory energy usage. Both goals are equally reinforced by the confusing scenario of a happy occupant who uses too much energy. With this grading system, we can see how well a controller strikes a balance between occupant satisfaction and energy efficiency.

An eight-week experiment in five offices demonstrates that LightLearn can learn the habits of its occupants and the state of the building's surroundings, then adjust its control parameters to achieve the desired effects. Overall, participants felt the illumination had improved slightly from before.

3.2. Network of wireless sensors and actuators for lighting control occupancy

Approximately 35 percent of current buildings in the EU are older than 50 years. These historic buildings, the majority of which have deteriorating infrastructure and insufficient operational resources, consume a substantial amount of energy. The retrofitting of these older buildings, however, gives an excellent chance to accomplish significant increases in energy efficiency while still preserving the built environment [4].

In modern buildings, automation relies on a combination of communication mediums, including both wired and wireless communication systems. Despite the fact that wired solutions are typically favored, wireless devices have grown more widespread as a result of advancements in communication technology, such as the speed and security of connections and the battery life. Batteries for sensors today have a lifespan of several years on average. Consequently, wireless sensors are already replacing or, in some cases, augmenting old wired systems, resulting in versatile and cost-effective building automation solutions.

In building automation, numerous wireless devices employing diverse protocols, such as Wi-Fi, ZigBee, Z-wave, and Bluetooth, are available. In addition to its versatility and adaptability, wireless gadgets of the present day are cost-effective and allow unobtrusive installation in existing structures without cables or cable ducts.

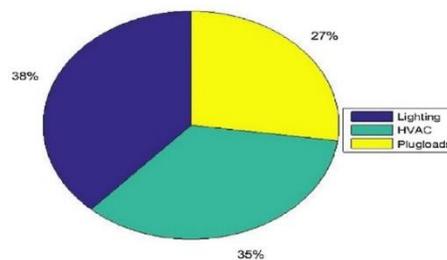


Figure 3. Distribution of annual power consumption among the three most common end uses: lighting, HVAC, and outlets [4].

The Wireless Sensors and Actuators Network (WSAN), which was once seen as expensive and immature for practical large-scale commercial applications, is now utilized in a variety of contexts.

Since lighting systems in open areas of the majority of commercial office buildings are frequently centrally controlled, WSAN promotes the deployment of optimal lighting systems. This dynamic system can alter the lighting in open-plan spaces according to the tastes and demands of the occupants in the most energy-efficient manner possible. By using the individual addressability of luminaires, they can be coordinated to give occupants with customized lighting for specific job functions, while ensuring that unoccupied rooms stay dark or at a background level of illumination.

The condition of structures with excellent insulation is contradictory. Heating and cooling systems do not consume the majority of the building's energy. Even when high-efficiency lighting solutions (LED) are utilized, illumination becomes a significant factor. Up to 30-35% of the annual energy used in buildings with strong thermal insulation is for lighting [4]. It is therefore crucial to seek out new techniques to lower the energy consumption of lighting in buildings, especially those that have already been completed.

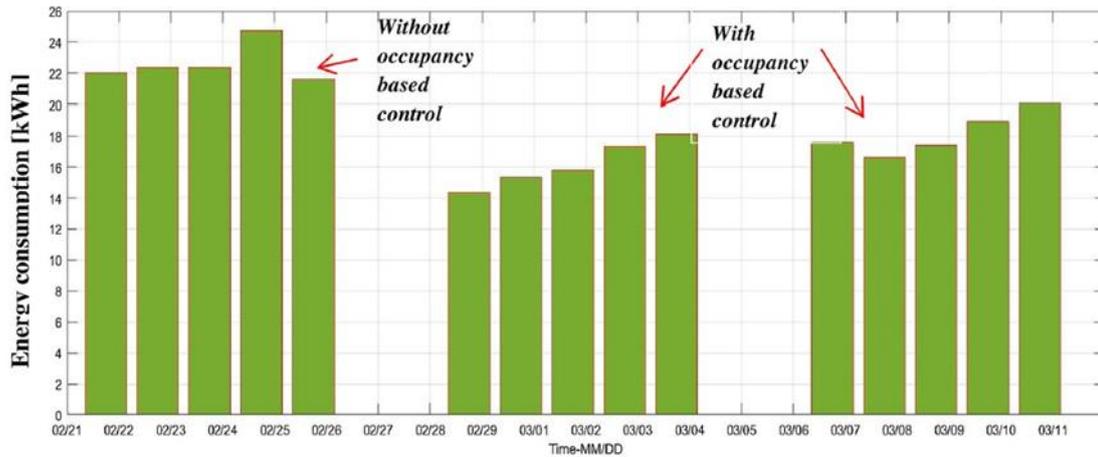


Figure 4. Daily illumination energy use [kWh] during the course of three weeks of studies [4].

Motion sensors in the space and pressure sensors in the seat (detection of the weight of the individual seated on the seat) were utilized and were programmed to only communicate data to an interface (gateway) when a change in state was detected. This meant that occupancy information was only provided to the gateway when the presence or absence of a human was recognized. Consequently, battery life is extended.

Existing building retrofitting is not a low-cost solution, but it offers significant energy savings. Thus, higher up-front expenses and a lack of understanding of the technologies and their potential might be considered as significant contributors to the relatively slow rate of building restoration.

In a medium-sized commercial office building, the feasibility of wireless sensors and actuators was assessed. In an open area of the office building, wireless sensors and actuators were installed for occupancy detection and presence-based lighting management. During the first week of the experiment with occupancy-based control, lighting energy usage was reduced by 28%. To preserve a pleasant relationship between the system and the user, the time delay between turning off the lighting and the occupant leaving the workstation was increased from 2 minutes to 5 minutes the next week, resulting in a 20% decrease in lighting electricity use.

3.3. User-centred lighting control based on video cameras

To gain a finer resolution of user position and activity, we examine a lighting control system based on data collected from a network of visible-spectrum video cameras. In the video camera, useful features are derived from the video image data. These characteristics from each camera are then collated by the central unit. The central unit can determine the location and activities of the user based on data collected from all cameras. The system then determines the best illumination level and sends commands to the lighting automation system.

The vast majority of studies employ sensors to monitor illumination levels and offer feedback for lighting management. This study is mainly concerned with the occupant. As a result, instead of using illumination sensors, it employs video cameras as room

sensors to acquire user position and activity as well as contextual data pertaining to the inhabitant.

A few tasks have been chosen to illustrate the provided topics. The selected activities represent a set of simple but frequent actions observed in ordinary users while seated in a room: - walking around the room, - sitting at a desk to study, - sitting on the sofa to watch television, - lying on the couch.

A module for image processing and a module for optimization construct the method. The image processing module uses a human silhouette-based 3D form reconstruction approach for logical reasoning on room occupancy. It has been demonstrated that silhouette-based 3D form has significant promise in a variety of applications [5], such as to construct the 3D silhouette-contour of a user and then generate a graphical model to determine the user's posture.

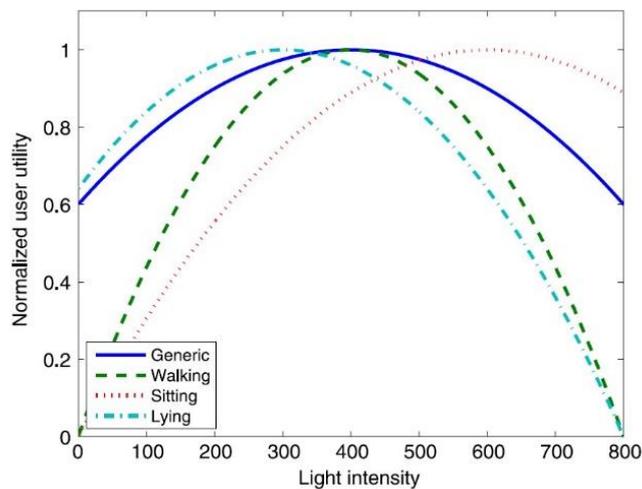


Figure 5. Multipurpose utility functions [5].

The analysis of human activity has been the subject of extensive research, but it remains a difficult endeavor due to variables such as the difficulty of dealing with an articulated human body model, changeable imaging settings, and the complexity of human activities.

There have been two lighting control algorithms proposed. The first consists of variable light intensity settings, while the second consists of on/off controls. For the light intensity control, it was expected that the light intensity can be adjusted constantly within a specific range, however for the on-off controls, it was considered that the lights can only be switched on or off.

The purpose of this study is to reduce lighting energy usage while preserving user satisfaction with lighting settings. To quantify a user's pleasure with the lighting condition, utility functions are utilized. A utility function establishes a relationship between light intensity and user happiness, represented by a value within a specific range. For various positions and occupations, distinct utility functions can be defined. For instance, the utility function in the area surrounding the desk may differ from the

utility function in the region surrounding the entrance, or we may have separate utility functions for sleeping and reading.

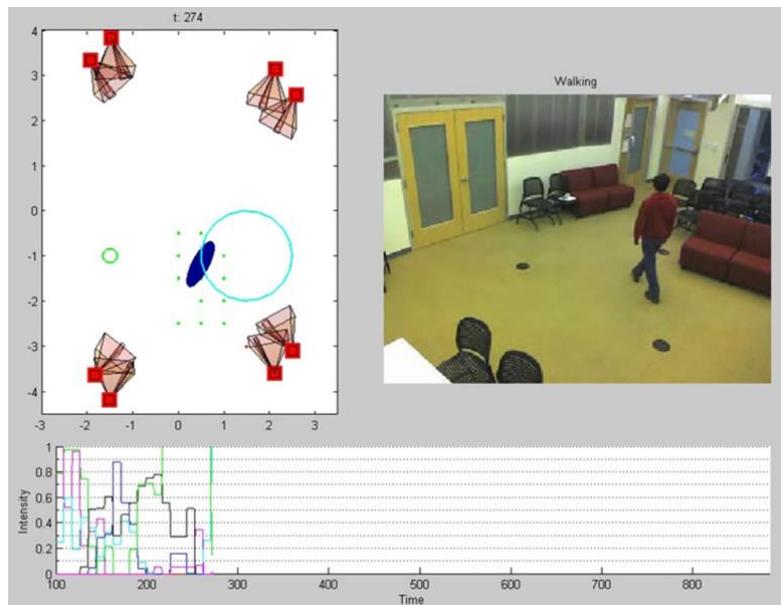


Figure 6. User-controlled light intensity snapshots [5].

The technology continuously monitors the area but only adjusts the lighting when the user's position or activity changes. Figure 5 depicts the flowchart of the light control system. When the system detects a change in the user's position or activity, it verifies the new utility values for every occupied point. The system reoptimizes the light control if one of the points has a lower utility value than the predefined value.

It is meant to expand the number of activities included in the human activity analysis algorithm. In this work, it was assumed that the light intensity delivered to the user can be computed; however, in the future, it is planned to include lighting sensors and real-time measurement of light intensity as a form of system feedback. Future development will also focus on enabling the user to customize the utility features for different tasks using a simple and intuitive interface. This can be accomplished, for instance, by a user-device interface by which the user offers incremental level changes in the system's lighting intensity for a certain position.

3.4. Intelligent lighting management system based on LifeLog

LifeLog is a record of a person's daily activities, including environmental behavior, activity, emotional and biological information. The usage of life logs enables the customization of the lighting environment to the user's characteristics. Nonetheless, such a tailored lighting environment has not yet been presented because the necessary data collecting and classification methods and a platform to synthesis these data are not yet physically feasible [6].

Sensors, lighting controllers, and control interfaces required for intelligent lighting control based on life logging were installed in a test space, a machine learning method was configured on a machine learning server, and a cloud-based platform for

implementing an optimal lighting environment was created by connecting these devices. This study's platform provides a tailored lighting environment by utilizing life logs, which are comprised of emotional information acquired by instant message (IM), text, activity information obtained using a location and activity tracker, and meteorological data.

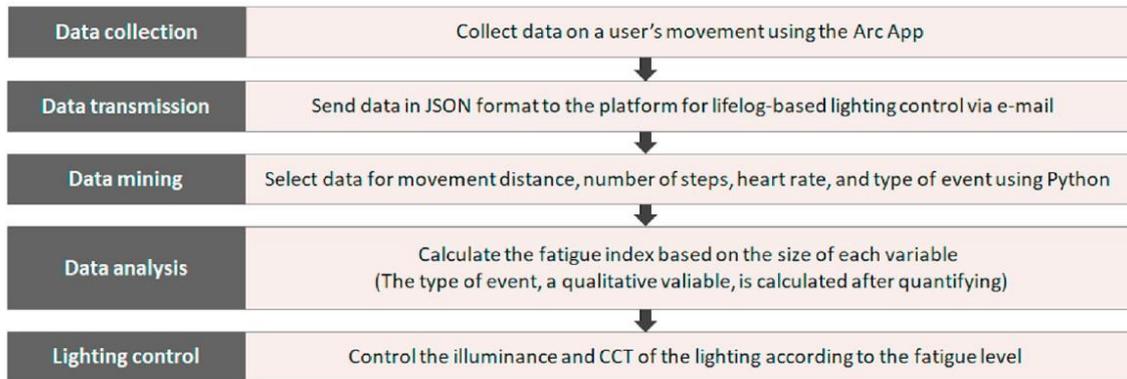


Figure 7. Method for intelligently regulating lights based on activity data [6].

LifeLog-based intelligent lighting control is proposed as a concept. It implements methods for gathering environmental data, emotional and activity information of users, as well as a system for recommending a suitable lighting mode for a particular individual based on an analysis of the information acquired about that individual.

A platform for intelligent lighting control based on lifelog aims to deliver an appropriate lighting environment based on the user's mood and situation, even without human input, by continuously collecting and storing lifelog data and by analyzing and learning from the stored data.

Smart lighting should be integrated with IoT, big data, artificial intelligence, and machine learning in order to provide a platform for lifelog-based smart lighting control.

The study proposes a lifelog-based smart lighting control technology that collects lifelog information via MI, activity, and weather data. Life log data are separated into: - emotional data, - activity data, - environmental information.

In Korea, the KakaoTalk social networking platform was utilized to adjust lights based on emotional data. The user sends the discussion text to an email account associated with the platform, and the email is examined for emotion analysis every 10 minutes. Therefore, there is a constraint in that user participation is necessary to collect text data, and emotion analysis cannot be conducted in real time.

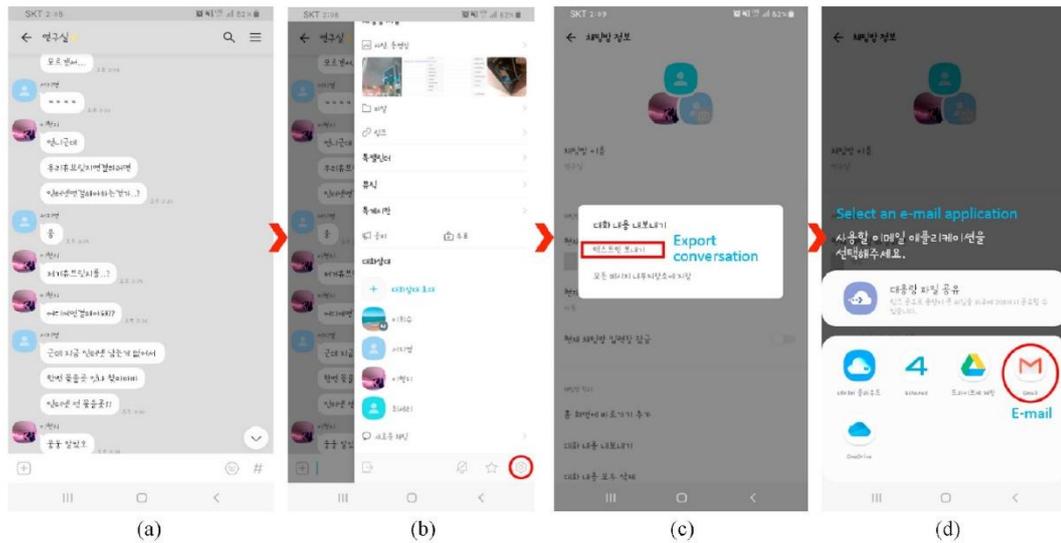


Figure 8. Procedure for Exporting Conversation Text from KakaoTalk for Emotion Analysis: To email a copy of your KakaoTalk chat history, you must first (a) open a chat window, (b) select the “Chat Window Setup” option, and (d) use the “Export Conversation” option [6].

For more precise emotion analysis in the future, physiological data acquired via wearable devices (e.g., heart rate, ECG, and PPG) should be added to the IM text and platform for intelligent, real-time control.

Importantly, the platform in the study goes beyond simple information like location, occupancy, and users' light usage patterns to recommend a lighting environment that is best suited to the user based on the result of a comprehensive analysis of users' emotional activity, activity, and environmental information.

Custom lighting is determined by three distinct types of data analysis:

In the first step, the user's mood is gauged by analyzing their IM chat logs for textual cues indicative of their emotional state. Once the relevant text has been extracted, it is translated from Korean into English using Node-RED and Google's Watson language translator. Then, IBM Watson's NLU is used to do an analysis of the user's emotions, categorizing them as either happy, sad, angry, scared, or disgusted.

The findings of this analysis of the five different emotions are then used to determine the optimal lighting mode for reducing the user's negative feelings via adjustments to the Correlated Color Temperature (CCT) and brightness.

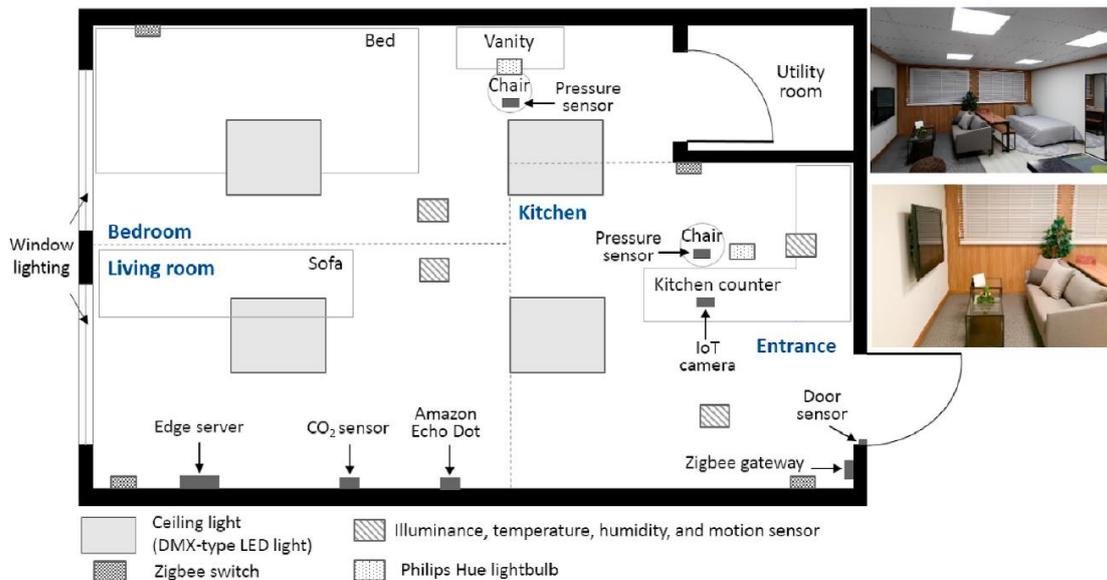


Figure 9. Plan and photos of the layout space [6]

Second, information on user behavior is gathered with the aid of a GPS and activity tracker and an Apple Watch. The data is sent to the platform through email in JSON format. Python is used to pick data on user attributes including walking distance, number of steps, heart rate, and the sort of event that occurred at the area visited by the user. The fatigue index is then computed after these factors have been quantified, and the user's tiredness is taken into account while selecting an appropriate lighting mode. Third, data from the Korea Meteorological Administration KMAweather's stations is used to compile statistics about the local ecosystem. The sky conditions used in this analysis fall into three categories: clear, cloudy, and entirely cloudy. Once data and forecasts for the desired region have been extracted from the KMA website using RSS (RSS provides this information as an XML file called RSS feed), Node-RED can use this data to adjust the DMX (standard for special lighting scenes effects) lighting in the sample space based on the weather outside. Using information about the user's emotions, activities, and the surrounding environment, this platform intelligently modifies the lighting to create the desired mood.

4. Conclusions

In recent decades, electric lighting has been a significant contributor to the rise in worldwide energy expenditures. Increasing the proportion of glazed building facades is a relative solution, since it raises additional difficulties of thermal and visual comfort, but the impacts on lighting consumption have lowered the energy savings of LED technology. [7].

The building sector faces enormous issues relating to energy efficiency, greenhouse gas emissions, and visual features, with health and well-being-related goals becoming increasingly ambitious.

Office spaces can easily achieve an annual energy consumption of less than 5 kWh/m² by integrating natural illumination effectively; lighting energy consumption can be cut

considerably. Advanced automation technologies have demonstrated the potential to deliver dependable solutions (e.g., self-learning or self-adaptive lighting systems).

To attain the planned goals for new buildings, rigorous architectural design for daylight and solar control will be required.

Current technological developments are characterized by integrative lighting, which will become widely used in projects, but only when technical expertise among specialized designers becomes more popular [8]. Artificial lighting will be activated in a "integrative" mode when natural light is insufficient, as a result of improvements in the efficiency of LED technology used in the manufacture of lighting sources, as well as the increased processing capabilities of automation system controllers. As a result of insufficient scientific and mathematical understanding and models, the use of daylight in integrative lighting is still fairly limited in practice. To make human-centered lighting an everyday activity, architects, designers, engineers, luminaire and automation manufacturers, and policymakers must make a concerted effort.

References

- [1] Lin B, Chen Z. Net zero energy building evaluation, validation and reflection – A successful project application. *Energy and Buildings*. 2022;261:111946.
- [2] Nagy Z, Yong F, Schlueter A. Occupant centered lighting control: A user study on balancing comfort, acceptance, and energy consumption. *Energy and Buildings*. 2016;126:310-322.
- [3] Park J, Dougherty T, Fritz H, Nagy Z. LightLearn: An adaptive and occupant centered controller for lighting based on reinforcement learning. *Building and Environment*. 2019;147:397-414.
- [4] Labeodan T, De Bakker C, Rosemann A, Zeiler W. On the application of wireless sensors and actuators network in existing buildings for occupancy detection and occupancy-driven lighting control. *Energy and Buildings*. 2016;127:75-83.
- [5] Lee H, Wu C, Aghajan H. Vision-based user-centric light control for smart environments. 2022.
- [6] Cho Y, Seo J, Lee H, Choi S, Choi A, Sung M et al. Platform design for lifelog-based smart lighting control. *Building and Environment*. 2020;185:107267.
- [7] Papinutto M, Boghetti R, Colombo M, Basurto C, Reutter K, Lalanne D et al. Saving energy by maximising daylight and minimising the impact on occupants: An automatic lighting system approach. *Energy and Buildings*. 2022;268:112176.
- [8] Gentile N, Lee E, Osterhaus W, Altomonte S, Naves David Amorim C, Ciampi G et al. Evaluation of integrated daylighting and electric lighting design projects: Lessons learned from international case studies. *Energy and Buildings*. 2022;268:112191.
- [9] European Commission. 2050 long-term strategy [Internet]. *Climate Action*. 2022 [cited 11 August 2022]. Available from: https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2050-long-term-strategy_en
- [10] The International Energy Agency I. Annual Reports || IEA EBC [Internet]. *iea-ebc.org*. 2022 [cited 11 August 2022]. Available from: <https://www.iea-ebc.org/publications/annual-reports>