A Smart Adaptive Lighting System for a Multifunctional Room

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***Abstract*—Young professionals and millennials who live alone or are living in small groups and seek practicality, trigger the trend of smaller, modular and micro houses and apartments which are faster and cheaper to build. Multifunctional or flexible room is one of the important parts of the home. This particular room needs well-designed lighting for comfort. It should give an adequate illuminance for every activity and even pattern of light. This paper presents the factors for developing the smart adaptive lighting system which can provide lighting comfort for the occupants. The simulation is being done in 5 scenarios in the LJMU BRE 2010 house model using DIALux Software with the dimmable type of LED independent luminaire. The proposed system structure uses a wireless sensor network (WSN) and big data processing as the main components. The design employs an Artificial Intelligence (AI) sub-system which has the capability to predict and adaptively regulate the illumination level based on the occupant needs or routine. The simulation shows that this system is able to give even lighting pattern for luminance values 200, 250, 300, 500, and 750 lux which are needed by the occupants. With the possibility of user-defined lighting values, this system can be developed to accommodate the needs of special groups of occupants such as the elder or disabled groups.**

Keywords—multifunctional room, flexible room, lighting comfort, adaptive methods, sensor network

I. Introduction

Multifunctional room or flexible room in the house or apartment is gaining popularity nowadays. For the house, the attractiveness of the multifunctional room is due to the fact that new houses in the UK are 32% smaller on average compared to what it was in the 1970s [1]. The housing shortage is the main reason for this. Some developers build a higher volume of houses in urban areas where the space cost are high. The same reason is also applied to an apartment. For the apartments, this flexible room is very common. Studios and micro-apartments have a single-area open floor plan and usually less than 600 square feet. Micro-apartments are designed to be space-efficient and the energy efficient factors are taken into consideration [2]. These conditions are about the same in every big city. In Europe, an average of 48%of the population live in apartments. The housing area in the UK is having an average of 76 square meters, smaller than Denmark which is 137 square meters [3]. It is common for young professionals and millennials to live alone or live in small groups. They are more practical and trigger the trend of modular homes which are faster and cheaper to build [1].

Smart multifunctional room, especially in the micro houses, are designed carefully. This is because of the combination of activities that can be done on single premises. The example of these is the kitchen and dining room combination, bedroom with tube area, indoor play area, multifunctional rooms, convertible bedrooms, and integrated home offices [4], [5]. In order to cope with this multifunctional rooms the lighting should be adequate and adaptive to all activities in the room. Lighting which is well designed can give lighting comfort for the occupants.

Human comfort is a condition of mind which expresses satisfaction or adaptation with the immediate environment. Human comfort can be divided into smaller aspect such as lighting comfort, acoustics comfort, air quality, thermal comfort, etc. [6], [7] and standardized in ISO 7730-2005 [8], ASHRAE 55-2013[9] and EN 15251-2007 [10]. Human comfort is analysed outdoors [11], [12] but mostly being studied indoors [6]. That is because a large proportion of the population spends 80-90% of their time in an artificial climate according to the research of NHAPS [13]. Human comfort is always of prime concern in the design process of buildings.

This paper presents the work in progress for developing the smart adaptive lighting system which can provide lighting comfort for the occupants in residential houses typically found in the UK. The comfort is achieved by giving even lighting pattern and variable illuminance level according to the occupant's activities. As the additional adaptive factor, the system will have the capability to address the individual needs for lighting illuminance level. This factor is important due to the unique individual perception for lighting especially for the elder or disabled user groups. The proposed system structure is using the wireless sensor network (WSN) and big data processing as the main components. With this approach, the system will have an Artificial Intelligent (AI) sub-system which capable to predict and adaptively regulate the illumination level based on the occupant needs. As a pilot stage of the proposed system, the light simulation model is implemented using DIALux simulation software. The results obtained for human lighting comfort are discussed in this paper.

II. Lumens Methods and Lighting Standard

Lighting comfort aims for providing uniform lighting in a room with an adequate amount of needed levels. This amount of illuminance is normally measured in lumens [14]. The design approach for the lighting system is by calculating the illumination using Lumen or Cosine method. This calculation is based on uniform geometry with the fixed intensity of all of the lamps [15]. The formula for calculating the number of lamps required according to the Lumen Method is shown in equation 1.

$$N = \frac{E*A}{n*F*UF*LLF} \quad (1)$$

where, N = The number of lamps required

E = Required illuminance (Lux level on a working plane)

A = Area of the room (m^2)

n = the number of lamps in every luminaire

F =Total lumens output per lamp

UF=Utilization factor (the function of the luminaire properties and room geometry)

LLF/MF = Light Loss Factor/ Maintenance Factor (the function of the depreciation over time of luminaire output)

UF can be referred from the table if the room index value is known. The room index computation can be calculated using equation 2

$$Room\ Index = \frac{(L*W)}{H_m(L+W)} \quad (2)$$

Where, L = room length

W = room width

H_m = the height of luminaire above the working plane

According to BS EN 12464-1:2011 which is the standard for Light and lighting for indoor workplaces, there is some light illuminance level which is becoming standard for indoor workplaces. This British standard is acquired from the European Standard. Although it is not directly targeted to the home, this work uses the illumination value to gain comfort, safety, and health for the occupants according to similar activities in the industry which are related to the activities at home. Some of the values are 200 lux for canteen, pantries, feed preparation, dairy, utensil washing, bakery preparation and baking, laundry ironing, lounges, entrance halls, and library bookshelves area. The illumination of 300 lux is used for bakery finishing, glazing, decorating, playroom, nursery, handicraft room, classroom, music practice, and computer practice. Higher illuminance, 500 lux is for sickbay, hairdressing, cutting, gilding, embossing, block engraving, work on stones and platens, printing machines, matrix making, writing, typing, reading, data processing, restaurant's kitchen, library reading area, classroom for evening classes, lecture hall, demonstration table, practical rooms, and handicraft room. The highest values for home activities is 750 lux which are for laundry inspection and repairs, art and technical drawing [16].

III. Human Comfort, Lighting Comfort and Adaptive Methods

The field of built environment science initially gained attention in the early 1920s when it became possible to control directly the microclimate of the indoor environment. In the old approach, the use of fireplaces to control the temperature was mandatory. In the second half of the nineteenth century, it was necessary to model the building as an open system and apply the laws of thermodynamics [17]. Various electronic controllers were developed which lead to the evolution of comfort monitoring. Fanger's comfort model introduced in the 1970s is the most thorough, critical review of thermal comfort for man and become a standard reference for thermal comfort. The quality of air movement and sophisticated models which map both physics and physiology of the human body were also developed to build the coherent, global thermal perception. These developments are also driven by energy efficiency [18]. In the twentieth century, the focus goes to human as the center point of the design in order to improve the health and comfort of occupants and their homes [17], [18].

The Fanger model which is referred to as the Predicted Mean Vote (PMV) / Predicted Percentage of Dissatisfied (PPD) is still facing challenges due to the parameters which cannot be captured in the model. The other methods which are the adaptive methods were introduced by Nicol and Humphreys [6], [7]. The adaptive model is formulated on the nature of humans who have the ability to adapt. The model then also acknowledged in ASHRAE-55 Standard [9]. This model can become the solution of the PMV which is not individual, not adaptable and has no input modification.

Naturally, people already have the adaptive act upon by the environment and have the behavioral actions clustered as self-adaptation category and adaptation to the environment category. Drinking cold beverages, less-sweating lifestyle, restraining physical activity level, changing clothes from warm to cool are some examples for self-adaptation. The activities for adaptation to the environment category are moving to a cooler location, opening or closing doors or windows. The personal parameters approach in human comfort is also applied to lighting comfort specifically. Behavioral actions related to lighting comfort are opening or closing operable curtains or windows, adjusting desktop or task surface and changing position or direction of furniture. Time is crucial for behavioral interactions. There are four typical time periods for the interactions; immediate, within-day, day-to-day and longer term [19].

Lighting comfort studies have been conducted on a wide range of applications. For office applications which considers the glare and the activity related to the computer, the value for vertical illuminance is 351.6 lux [20]. The framework review for personalized control [21] is also presented to make the system perform the automatic task whilst still consider the comfort. The study also focused on the implementation on the on-off system to lower the energy usage [22] [23, 24] so that the lights and the other related parameter such as blinds can be controlled to support the energy saving. Some approaches are deployed to gain better control for lighting, for example, the use of artificial neural network (ANN) to simplify the model of parameter tuning [25] and the use of reinforcement learning to gain the knowledge on the schedule-based and occupancy-based control scenarios and use it to control lighting and blind [26, 27].

In the previous work, the lamps are not individually controlled in association with the normal daylight coming from windows. Most of the work use the on-off lamp scheme. The result is non-uniform intensity and still can trigger the discomfort situation especially when there is another source of light which cannot be controlled. Therefore, this system will use the dimmable LED as the controlled artificial light source in the absence of the natural light. The dimmable LED can also be used to balance the uneven pattern of natural light. Due to the presence of natural light which is too bright, the blind is used to block excessive light. The use of the dimmable LED also will be beneficial to set the different lighting scenarios to adapt to the need for elder or disabled occupants. The individual control of the lights and blinds are getting the benefit of the use of the WSN.

IV. WIRELESS SENSOR NETWORK (WSN)

In recent years, due to the growing low-cost sensing solutions, the provision of lighting and thermal comfort has been widely increased to existing and future smart buildings to aid productivity, health, and wellbeing. Many sensors are potentially used widely in the home comfort system with easier installation and control. The WSN will change the approach of the system solution. WSN is a network of sensors with unique characteristics. The nodes have limited power, limited processing power, and transmission. There might be a connection to more powerful servers (cloud). The circuit also relatively simple but having enough power to do their tasks. The use of these sensors beginning to be very common and sometimes being called the internet of things devices. Their roles and tasks are unique and specific to overcome their challenges which are low power, low price, limited range and scattered node position [28].

Zigbee is one of the WSN which is suitable to form a real-time control system [29], [30]. Zigbee can form a mesh network which capable of giving fault tolerant capability and sufficient distance of data transmission for distributed indoor controller [31].

V. SYSTEM DESIGN

A. Infrastructure Design

The approach of the infrastructure design is the use of the WSN to simplify the installation and give the ability for system expansion and scaling. The infrastructure design can be seen in Figure 1. The upper tier is a services tier (cloud-based services). This entity consists of the database server and application server. The database server is used to store the sensor reading data and the preference data of the occupants. The sensor data will be used to do the calculation for recommendation setting and the preference data will be used to push the scheduled activity and setting to the controller. The application server is being used to give access to the administrator for setting up the rule and maintain the system. The user can also log in to the system from remote areas to control the system from the distance if needed.

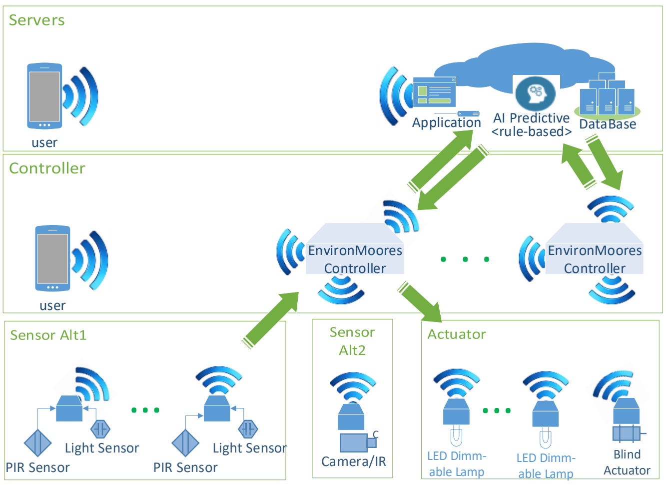

Fig. 1. The Proposed System Diagram.

The middle tier is the controller located in the house or apartments. This controller has the ability to do the local calculation for immediate response to the user requests or providing the best comfort setting to the user. This tier is also able to submit or route the data if the controller cannot do the fast calculation for the massive data that require to be sent to the cloud for cloud processing. On the contrary, the controller is also able to conduct action or command sent by the cloud to the actuator. The connection of the middle tier to the cloud can be done using Internet Protocol. This connection can be in the form of a cellular data connection or optical fibre. User can also have direct access to the controller via their smartphones through their Wi-Fi or Bluetooth.

The lower tier is the sensors and actuators. These sensors and actuators are connected to the middle tier by the distributed controller (WSN). The sensors can be a passive infra-red sensor to detect the presence of occupants and a light sensor to measure the illumination values. Another type of sensor is the camera or thermal camera to get identical data. The actuators for this system are the independent LED for lighting and the blind actuator for controlling the blind automatically. Another actuator such as window tinting can also be used for this system.

B. System Flow

The system works by the user trigger. The trigger can be in the form of user request from the application in their smartphone or their presence. The system flow can be seen in Figure 2. When the user enters the premises, the system will give the command to set the luminance for even pattern for 200 lux. If the user has set the routine, then the system will lit the lamp according to the pre-set value. This values will form rule-based and case-based reasoning to build the core artificial intelligent (AI)[32]. The system will react based on the set of rules and knowledge gathered prior to the event. If no data found then the system will give the prediction of the activity based on the location of the work pane of the user. User can also give correction directly from their smartphone at any time. This feature will make the system adaptive to user need. This value can be stored in the system database to create the user profile. The system can also adapt to the user activities which need a different set of lighting illumination value. If the user leaves the premises, the system can automatically switch off the LED illumination to conserve energy. This can also be overridden by the user.

C. User Interface Design

The user interface of this system is designed as simple as possible and having the capability to be operated elder or disabled occupants. After the user logs into the system, the user can set the preferred illumination level if needed and stored in the preference data. The detail of the illumination values is given just to inform the user on the standard values mentioned in BS EN 12464-1:2011.

VI. SIMULATION RESULT AND DISCUSSION

A. Premises

The simulation of the system uses the LJMU Exemplar houses for the simulation model. These houses are the research houses built in the area of LJMU campus to conduct the trial for the new technology to be implemented in the different house's era. There are three houses to represent the 1920s era, 1970s era, and 2010s era. The lighting simulation model is built based on the 2010s era house. The picture of the

LJMU Exemplar houses, the CAD drawing of the 2010s era house and the lighting model for the multifunction room in the 2010s era house can be seen in Figure 4. The multifunction activities in this house cover the function of the kitchen, dining area, reading area, handicraft room, art room, and other similar functions.

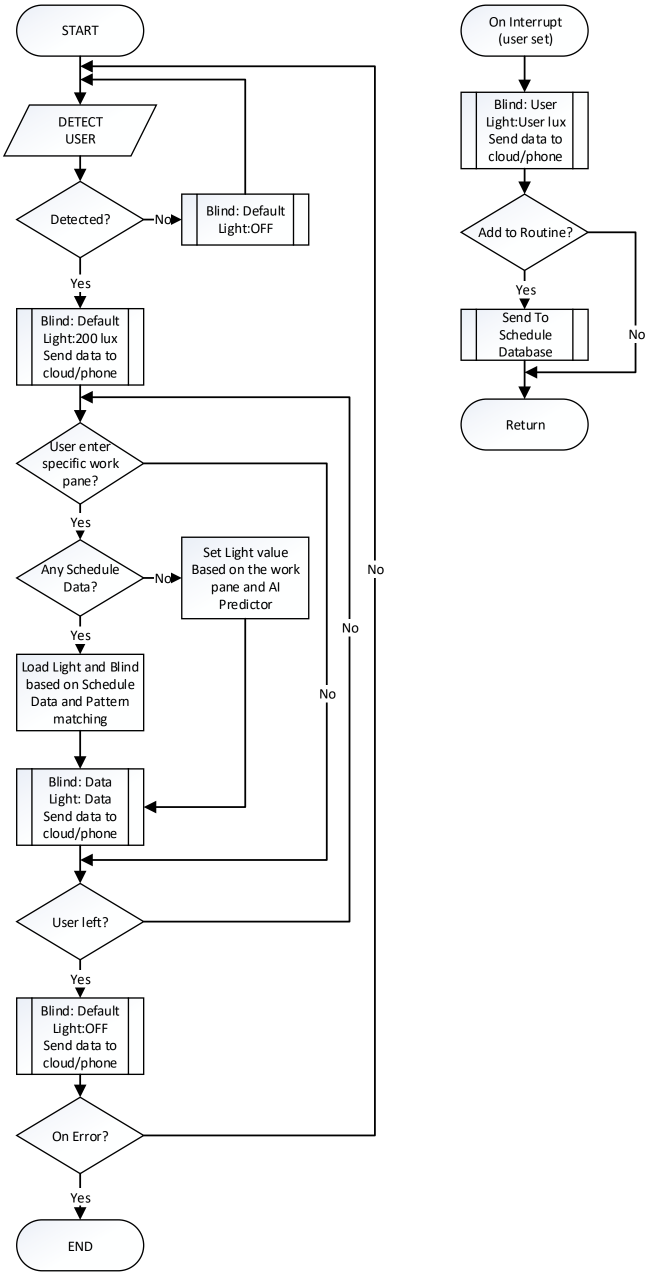

Fig. 2. The Proposed System Flow Chart.

B. *Simulation Parameters*

The simulation parameters are very crucial for this lighting simulation. For the natural light, the latitude and longitude of the location, reference sky, the date and time will decide the pattern and the illumination parameter of the natural light. The result of the pattern used in this simulation can be seen in Figure 7. For the artificial light, the parameters shown in Table 1 will decide the behaviour of the artificial light. These parameters are based on the real physical property of LJMU Exemplar houses. In order to make the model more realistic, dimmable commercially available LEDs will be used. The number of the luminaire is calculated using equation 1 and 2, with 8 as the result. The maximum value of the illumination is 750 lux according to the standard from BS EN 12464-1:2011[16]. The system is designed to provide up to 1000 lux so that the occupant who requires higher illumination value can be accommodated for adaptive purposes.

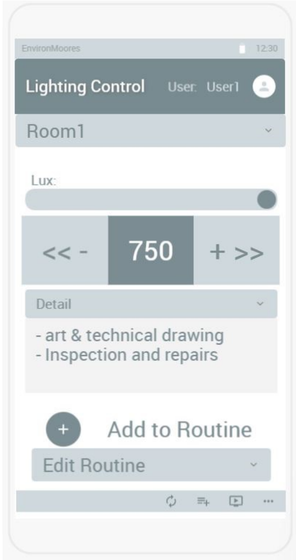

Fig. 3. The Proposed User Interface for Lighting Control

Fig. 4. LJMU Exemplar Houses (Top), The CAD Drawing and Lighting DIALux Model (Bottom)

C. *Simulation result*

The simulation is being done in 5 scenarios. The first scenarios are a natural light simulation. Using only the natural light, the light pattern will create discomfort since the light produces an uneven pattern. This will result in visual fatigue or sometimes dizziness if occupants keep staring at the different scene with different lighting level. The result of this pattern can be seen in figure 5. If the natural light is too bright the controller should activate the blind control or glass tinting to lower the illumination level and avoid glare.

Table 1. Simulation Parameters and Values based on LJMU Exemplar Houses

Simulation Parameters	Values
Room Size	$13m^2$ (5m x 2.6m)
Ceiling Reflectance	75%
Wall Reflectance	50%
Floor Reflectance	20%
Maintenance factor	0.80
Clearance Height	2.9 m
Work plane Height	0.76m
Window size	0.83 m^2 (1.82m x 1.2 m)
Number of Luminaire	8
Luminaire type	Thorn Lighting Dimmable Novaline LED3500-840 HFI E3 WH 96643238
Max Illumination	< 1000 lux
Site Location	Liverpool, Eng
Site Latitude	53.41° (53.41°N)
Site Longitude	-2.98° (2.98°W)
Time zone	(UTC+00:00) Dublin, Edinburgh, Lisbon, London
Reference sky type	Average sky

The second up to the fifth scenarios are all using the same natural light in the first scenario. This is to show that the natural light can still be used to lower the use of artificial light power so that the energy can still be conserved without having to make the lighting pattern become uneven. Figure 6 shows the lighting pattern for 200 lux illumination. It is still distributed evenly with 2 sources of lighting which are artificial and natural light. The other simulation result for 300 lux, 500 lux, and 750 lux can be seen in Figure 7 to 9 respectively.

As shown in Figure 3, the occupants are being given the flexibility to increase or decrease the illumination level by selecting the + or – menu. The user can also store the value for routine pre-set, which become the occupants' feedback for the system. In this simulation, the feedback is represented by the intermediate value of 250 lux. This value represents the decreased value from 300 lux and the increased value of 200 lux. The design also allows the flexibility if the occupants want to increase the value of more than 750 lux. The value is limited to 1000 lux maximum due to the functionality and economical reason.

D. Discussion

Based on this simulation result, the percentage of the LED luminaire power are tabulated to form table 2. This result shows that the independent controlled LED is able to perform needed illuminance level by controlling each LED luminaire and produce an evenly lighting pattern. The occupants also still have the capability to increase or decrease the illumination values which make the system adaptive to the personal lighting needs to achieve good visual performance. Hence the lighting comfort can be achieved using this system. The special needs of the occupants can also be fulfilled using the adaptive approach of the system. However, this system is only focused on the illumination value. The other aspect of lighting approaches such as giving different lighting colour is not the focus of this paper.

Fig. 5. The uneven pattern of the ambient sunlight light simulation at 06:00 AM, May 2019 in DIALux Evo 8.1.

Fig. 6. The even pattern simulation result from combining the sunlight (06:00 AM) and artificial light of the smart adaptive lighting system for 200 lux illumination in DIALux Evo 8.1.

Fig. 7. The even pattern simulation result from combining the sunlight (06:00 AM) and artificial light of the smart adaptive lighting system for 300 lux illumination in DIALux Evo 8.1.

Fig. 8. The even pattern simulation result from combining the sunlight (06:00 AM) and artificial light of the smart adaptive lighting system for 500 lux illumination in DIALux Evo 8.1.

Fig. 9. The even pattern simulation result from combining the sunlight (06:00 AM) and artificial light of the smart adaptive lighting system for 750 lux illumination in DIALux Evo 8.1.

Table 2. Simulation Result

Illuminance (lux)	*LED Power (in %)*							
	L8	*L7*	*L6*	*L5*	*L4*	*L3*	*L2*	*L1*
200	*11*	*11*	*22*	*22*	*22*	*22*	*22*	*22*
250	*15*	*15*	*25*	*25*	*25*	*25*	*25*	*25*
300	*30*	*30*	*40*	*40*	*40*	*40*	*40*	*40*
500	*57*	*57*	*65*	*65*	*65*	*65*	*65*	*65*
750	*87*	*87*	*92*	*92*	*92*	*92*	*92*	*92*
<1000	100	100	100	100	100	100	100	100

VII. Conclusion

This paper developed a solution based on the adaptive approach of the system which can accommodate special occupants' needs. The system is simulated using DIALux software with the real parameters and components. The system uses the WSN and Big Data to make the system smart enough to give lighting comfort to the user. The dimmable LED luminaires are used to create even lighting pattern. Several illumination values are simulated to show that the system is able to provide even pattern of lighting on each level of lighting illumination. The simulated system is found satisfactory. This system can be extended to cope with other occupants need. Further work is in progress to analyse the Big Data and Artificial Intelligence scenario which will perform best for the system.

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