Smart system to control lighting in a smart library

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ABSTRACT

Smart light controllers revolutionize energy efficiency and convenience by controlling lights with precision. The main problem with such control structures is that the existing lighting systems are outdated and inefficient in places such as libraries, leading to unnecessary energy consumption. In this study, we propose the implementation of an intelligent light-emitting diode (LED) lighting control system that optimizes energy in libraries. The system utilizes passive infrared (PIR) sensors and a counter mechanism. When an aisle is occupied, the LEDs operate in highlight mode; however, they switch to medium-light mode when no presence is detected for a predetermined period. For this process, we propose a new control system with the random forest prediction algorithm for displacement patterns. We also designed a mathematical algorithm with three matrices derived from previous work on lighting. The algorithmic process is applied to ensure that the proposed system has enhanced maintainability, the simulation methodology generated scenarios based on occupancy data collected from real library environments, MATLAB was used to create dynamic simulations that reflected these user behaviors, with the power consumption of each LED calculated over an eight-hour operating period, the proposed system achieves potential savings between 23% to 39%.

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1. INTRODUCTION

The significant industrial growth observed in various countries has had a detrimental impact on the environment. This has light-emitting diode (LED) to heightened awareness of the associated effects, prompting a surge in demand for environmental protection measures, particularly those related to green energy. In the residential sector, energy consumption and demand are increasing daily. There is a growing interest in more efficient electrical equipment, particularly in light of the rising oil price, which has LED to an increase in electricity prices [1].

Furthermore, rapid population growth presents a significant challenge for countries in terms of meeting production and transmission needs [2]. In the United States of America (USA), energy consumption in the building sector reaches 40% [3]. Consequently, the demand for lighting solutions that minimize energy consumption and the evolution of lighting technology have a significant impact on the lighting industry [4]–[6]. Consequently, numerous studies have demonstrated that the regulation of lighting through sensors can decrease energy consumption and that sophisticated techniques can enhance energy savings beyond mere on/off control [7]. Additionally, research on lighting has increasingly prioritized the integration of systems and interconnections with human and market needs, indicating the projected growth of the lighting industry to 44.3 billion dollars by 2025 [8].

It is common practice for library lighting systems to be fully illuminated throughout operating hours, irrespective of the occupancy or usage patterns observed in individual aisles. This results in considerable energy consumption, as lighting remains operational even when unoccupied library sections. The inability of traditional on/off switch systems to adjust to real-time occupancy results in inefficient energy use in these large spaces. In light of increasing energy costs and the growing environmental impact, enhancing the efficiency of lighting systems in libraries is becoming increasingly crucial. The utilization of networks and sensors illustrates that the methodologies employed in lighting systems offer notable economic advantages, particularly when the room is unoccupied or the ambient brightness is excessive. The lighting system's ability to optimize energy usage is a significant benefit. In this context, Byun *et al.* [9] proposed a lighting control system that considers both occupant satisfaction and energy efficiency. This is achieved by controlling lighting via spatial characteristic parameters and occupant behavior. Recently, several research proposals have been proposed that can be broadly classified into two categories: wired systems and wireless technology-dependent systems. The implementation of wireless technology facilitates the realization of energy savings in smart buildings to a greater extent than wired technology [10]. Furthermore, the combination of wireless technology with LED lighting has the effect of reducing the consumption of electricity. This technology is used in a variety of domains within the industry, as evidenced by the numerous applications documented in the literature [10].

In this context, a lighting control system developed in [11] that incorporates an LED, a light sensor, a motion sensor, and an interface for communication. The data obtained from the sensors is utilized to analyze user behavior, to determine the optimal power control strategy. On the other hand, a proposed system [12] of lighting for the street environment that employs ZigBee technology to regulate system parameters. The system was observed to result in a 70.8% reduction. Conversely, Han *et al.* [13] designed a smart system control for lighting based on wireless network sensors, illuminance, and light uniformity. Additionally, Kapoor *et al.* [14] presented a lighting system for a classroom setting. The system consists of a passive infrared (PIR) sensor to detect movement and a two-channel relay module connected to an Arduino Uno microcontroller to control lighting. The system is designed to turn on the light when someone is present in the classroom and turn off the light when no one is in the room. A comparable study was presented in [15], in which the PIR detects individuals through body temperature. A system proposed in [15] that employs two PIRs: one to detect the entrance of individuals and the other to detect their exit from the entrance.

The system's fundamental principle is that the level of brightness is correlated with the number of people present. However, a potential limitation of this system is that when the number of people is relatively low, the brightness may not be sufficient to adequately illuminate the area. The lighting in a library is frequently controlled by a switch that allows for on/off operations, in contrast to other public spaces, which exhibit distinctive usage patterns that render energy optimization a more intricate undertaking. The number of people in the library at any given time varies considerably from one area to another and from one time of day to another. People move between aisles or congregate in certain areas, which means that the occupancy of different sections is irregular.

These usage characteristics necessitate the implementation of an intelligent, dynamic lighting system that is capable of adjusting lighting levels in accordance with the specific occupancy of each aisle, thereby ensuring that energy is utilized only when necessary. The primary challenge associated with smart lighting is its potential to reduce energy consumption in settings where the movement of occupants is not particularly complex, such as offices, toilets, and corridors. While these systems offer cost-effective and convenient installation, they are not well-suited for complex scenarios that require analysis of human movement, such as libraries.

The implementation of strategies to increase the efficiency of lighting in libraries has the potential to significantly impact both energy conservation and operational costs. The implementation of a smart lighting system in such spaces has the potential to reduce energy consumption and align with broader sustainability goals. In light of the considerable energy requirements of lighting in libraries and the potential for intelligent systems to adapt lighting according to occupancy, there is a clear necessity for targeted solutions that increase energy efficiency in library settings.

This article proposes a sustainable smart lighting system tailored to the unique needs of libraries, which are considered complex environments concerning human movement. The proposed system is a low-cost, easy-to-install solution that can save 23% to 39% of energy by controlling the lighting in the library via four PIR sensors. When a person enters an aisle, the LEDs in that aisle will be in a high-light mode, and the counter will increase by one. Conversely, when a person leaves an aisle, the counter decreases by one. When the counter reaches zero, the LEDs are in medium-light mode. Additionally, the brightness of the aisle LEDs will be modified concurrently with the transition between high and medium modes, thereby providing a high-quality visual representation of the aforementioned change. In other hand the application of the smart libraries uploaded send the information of clients displacement to the controller, it analyze the speed of the client between two aisles when he researches the wanted product and the time when the client stay without movement before enter to the aisle, these speed and time are classified using the algorithm random forest to precise the degree of importance of the aisle so if the degree of importance too high, the lighting switch to high-light before that the client enter to the aisle.

Furthermore, the maintenance method proposed for our system is straightforward and easily implementable. It enables expeditious error detection through a matrix depicting the status of all the LEDs in the library. Furthermore, it allows for the prediction of inadequate lighting levels in aisles and facilitates the testing of individual LEDs for maintenance purposes. This paper represents an extension of the research presented in [16]. The study in [16] demonstrated a 10% reduction in energy consumption, a promising outcome for public spaces such as parking lots. Moreover, the objective of [16] is to synchronize lighting to minimize energy consumption. However, our system is designed for smart library lighting applications.

It is based on the detection of the PIR sensor, and the energy-saving lighting is related to the counter in the aisle. The LEDs turn to the medium mode of lighting even if there are no people in the aisle. This adds a precision layer to our system control, which differs from [16] in that there is a misjudgment in the absence of a person in the area. This research advances the field of smart lighting by incorporating machine learning with PIR sensors in three major ways.

First, current systems primarily provide binary occupancy detection (in other words, only "occupied" or "unoccupied") either through direct detection of individuals via a PIR sensor or indirect detection via counter measurement methods. In contrast, the proposed system offers aisle-level granularity, which allows for the independent and fine-grained control of individual lighting zones within complex spaces, such as libraries, in a way that previous research has not. The finer precision afforded to the proposed system enhances the system's ability to adapt to heterogeneous occupancy patterns.

Second, while the use of machine learning in previous studies has been limited to occupancy detection, the current study's implementation of a random forest model provides for the predictive assessment of aisle importance based upon user displacement behavior. This allows lighting-related decisions to be made in a more anticipatory rather than reactive manner. As such, the approach improves the ability to determine aisle importance before occupants enter the area.

Third, and most critically, the matrix-based maintenance and verification method offered by the current study is all but non-existent in smart lighting literature. This method allows for the evaluation of lighting quality for all zones. It greatly improves the speed at which faults can be diagnosed and LED-level failure can be identified, resulting in an overall increase in the reliability and maintainability of the smart lighting system.

Therefore, the contributions offered by the current research cannot be clearly associated with other systems that have previously employed PIR sensors for occupancy-based control of lighting systems. The current study integrates three new concepts into one cohesive method that clearly sets it apart from current occupancy-based lighting control methods. The following sections are organized as follows: section 2 outlines the methodology, section 3 details the evaluation framework and results, and discusses the findings in depth, and section 4 presents the conclusion and proposes potential directions for future research.

2. METHOD

This study presents the development of an intelligent lighting control system designed for use in library settings. The system's primary objective is to dynamically adjust lighting based on the occupancy of aisles, thereby reducing energy consumption while ensuring sufficient illumination. The system is operated through the use of PIR sensors, which are installed at entry and exit points in library aisles.

These sensors detect movement within the area and subsequently adjust the light levels via this detection. The approach includes the configuration of the system, placement of sensors, logic of operation, and simulation. Figure 1 displays an application context for the suggested system.

The system setup entails the placement of four PIR sensors in each aisle, which are situated to detect both ingress and egress movements. The lighting in each aisle is controlled independently, with LED technology enabling switching between high and medium-light modes based on the occupancy of the area. The sensors are arranged in pairs, with two positioned at the aisle entry and two at the exit.

This configuration enables the system to accurately track the number of occupants in each aisle. A control circuit monitors occupancy in each aisle to determine the optimal lighting mode. The circuit integrates data from the client's phone application, such as the client's velocity (V') between aisles during product searches, and the stationary time (T') before entering an aisle. The random forest algorithm, which is described in detail in Algorithm 1, is employed to analyze relevant input features—such as client movement patterns, stationary time, and aisle-specific sensor data—and to generate a prediction of the relative importance or priority of each aisle for the client.

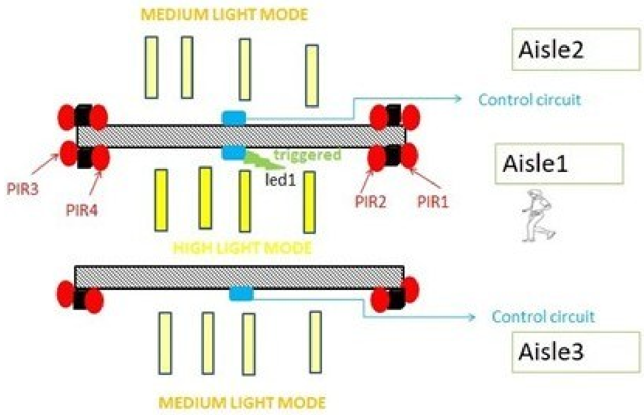

Figure 1. Presentation of the proposed system

Algorithm 1. Random forest
Target variable: importance degree of the aisle for the client (binary variable: 1 for high importance, 0 for low importance).
Features: the speed V', the time T'.
A trained random forest model (Cj) consisting of B individual decision trees, each constructed using a bootstrapped sample and a random feature subset. Procedure:
Input: the environmental conditions and occupancy for the prediction instance. For each decision tree (Cj) in the random forest:
i) Randomly select a feature subset from the input features.
ii) Use the selected features to traverse the decision tree:
Start at the tree's root node.
For each node in the tree:
Check if the node corresponds to a leaf. If it does, take the predicted status importance degree from that leaf and move to the next tree.
If the node is not a leaf, evaluate the split condition based on the random feature subset and the input features. Follow the left or right branch based on the outcome of the split condition.
iii) Repeat steps a-b for all B decision trees in the random forest. Aggregate the predictions from all decision trees.
Output: the final prediction

The sequence of the two PIR sensors is employed to ascertain whether an individual is entering or exiting the aisle of the books. If PIR sensor 1 or PIR sensor 3 detects the presence of the individual first, the individual is deemed to be entering the aisle of books 1, resulting in an increase of one in the system counter. Conversely, if PIR sensor 2 or PIR sensor 4 detects the presence of the individual first, the individual is identified as exiting the aisle of books 1, leading to a decrease of one in the system counter. In the initial step, the counter is zero; when someone is displaced to aisle book 1, the counter increases by 1. Subsequently, the LEDs in aisle 1 receive the trigger signal, transitioning to high-lighting mode. The LEDs in the same aisle exhibited synchronous behavior, whereas the LEDs in the other aisles were not influenced by the trigger signal in aisle 1. If the PIR sensors 1, 2, 3, and 4 of the preceding LED fixtures are unable to discern the presence of a person, the lights are encouraged to transition to a medium illumination level after 20 seconds, such that no one is in aisle 1, and the system counter associated with aisle 1 will equal 0 again. The conditions of the non-detection of the PIR sensors, the approach of persons, and the system counter equal 0 must be met for the LEDs in aisle 1 to be set to a medium level. This strategy serves to prevent a reduction in luminosity when an individual remains in aisle 1 for an extended period. If the system counter does not reach a value of zero and an individual is identified as approaching aisle 1, the counter will undergo an increase of one unit. However, this alteration does not affect the luminosity of the LEDs. A similar process occurs when an individual is detected. In a displaced position on either aisle 2 or 3, the counter will undergo a decrease of one unit in this instance. In this system, the light intensity for each lighting point in the library is verified. If we consider X grids, y users, and n LED devices, which we refer to as LED1, LED2, and LEDn, respectively, the X grids represent the network area and are named j1, j2, ..., jx. For each grid, there are four PIR sensors. However, as the users are mobile, the intensity of the LED lighting is denoted by $s(led\ i)\ i = 1, \dots, n$, which is described by (1) [17].

$$s(led\ i) = LED(i) \times Pelectrical(i) \quad (1)$$

Where $s(led\ i)$ is the luminous flux (light output) in lumens (lm), $LED(i)$ is the luminous efficacy of the LED in lumens per watt (lm/W), representing the efficacy of converting electrical power to light, and $Pelectrical(i)$ is the electrical power supplied to the LED in watts (W).

It is assumed that the aisle contains LED lights, and that the intensity of the lighting detected by the sensor in the aisle is represented by the variable $s(aisle(i))$, where $i = 1, \dots, X$. The (2) is then derived [17].

$$s(aisle(i)) = Sum(s(led(i) \div 4) \times 3.14 \times d(i) \quad (2)$$

Where $s(aisle(i))$ is the luminous flux of the ith LED (in lumens) and $d(i)$ is the distance from the ith LED to the sensor (in meters).

To guarantee optimal visual clarity for patrons within the library setting, we have established a matrix of lightness levels, as in (3) [18].

$$Stotal = s\big(aisle(i)\big) \times W + Ssun \quad (3)$$

Where the weight matrix W, 1×X column, $W = [w(1), w(X)]$ where the weighted factors $w(i) i = 1, \dots, X$ are between 0 and 1, and $Ssun$ is the matrix of natural lightness, and $s\big(aisle(i)\big)$ is the intensity of the lighting matrix detected by the sensor in the aisle.

Furthermore, Algorithm 2 shows the algorithmic process is evaluated to ascertain the degree of lightness across all grid elements within the library, and Pr-aisle represents a matrix of 1×X column, indicating the presence within the specified aisle. Additionally, light-max denotes the maximum lightness value, whereas light-medium represents the medium lightness value.

Algorithm 2. Matrix-based lightness quality evaluation in library aisles
```
For j from 1 to X do
   If (Pr-aisle(j) == 1) and (Stotal(j) == light-max) then
      Quality = good
   Else if (Pr-aisle(j) == 0) and (Stotal(j) == light-medium) then
      Quality = good
   Else
      Quality = not good
   End If
End For
```

In the event of a deficiency in quality, we streamline the maintenance process by focusing on the LED, as the degree of lightness affects the quality. To achieve this, we utilize a single LED in aisle j in high light mode, while the remaining LEDs are deactivated. This allows us to verify that the Stotal(j) value is equal to the ratio of light-max/k. If this ratio is correct, it indicates that the quality of the LED is satisfactory. However, if the equality is not accurate, it can be concluded that the LED under test is the source of the problem. This same process is then applied to all the LEDs in each aisle in the library.

The proposed model was evaluated through the use of MATLAB simulations, which were employed to model the movement of users across library aisles. The key parameters under consideration were the frequency of aisle occupancy, power consumption in high- and medium-light modes, and duration of aisle usage. The power consumption of each LED was calculated via predefined equations, and the overall efficiency of the system was evaluated by computing the energy consumption across a range of scenarios.

Although PIR sensors form the basis for occupancy detection, their reliability will be limited by a number of in-built limitations. These limitations can lead to false positives (detecting occupancy when there is none) and false negatives (failing to detect an actual occupant). The main sources of these indicators will be ambient temperature fluctuations, the same thermal characteristics of human bodies and their surrounding environment, and obstructions that obstruct the normal propagation of infrared radiation.

To evaluate these limitations, we propose a methodical error analysis. The method will involve computing standard statistics including the false positive rate (FPR) and the false negative rate (FNR) by comparing the sensor output to the ground truth occupancy data. To make the system more robust, a redundancy strategy has been introduced to allow PIR sensors to be integrated with other types of sensors with complimentary sensing modalities (such as thermal or illuminance). This will allow cross validation of occupancy data and reduce the incidence of faulty occupancy data. Data fusion can be performed through filtering on the data or implemented using random forest to enhance accuracy of classification. Finally, using established metrics, the overall performance of detection will be evaluated for each method, allowing for the evaluation of the reliability of the system under varying conditions of occupancy. This approach will provide an increase in reliability for the lighting control system, while also addressing the limitations of operation for PIR based detection. The simulation considered an eight-hour operational period, assuming varying occupancy patterns, to measure the system's potential for energy savings under diverse conditions, and Figure 2 presents the principle of the control system for lighting in an aisle.

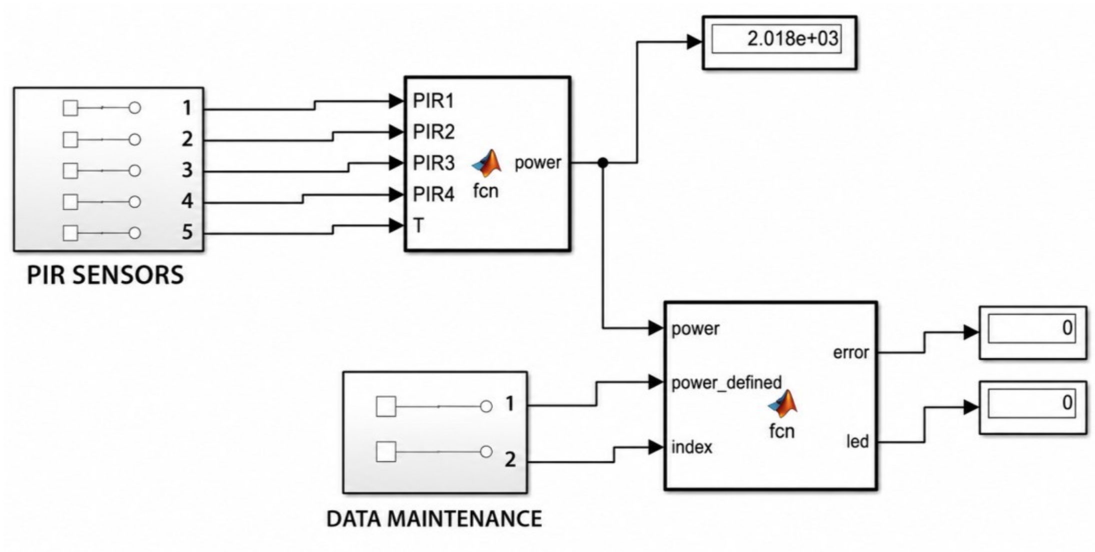

Figure 2. Simulation of the proposed system

3. RESULTS AND DISCUSSION

The simulation methodology generated scenarios based on occupancy data collected from real library environments. User movement patterns were represented by variables such as the frequency of aisle occupancy, average time spent per aisle, and lighting mode. Transitions between high and medium levels. MATLAB was used to create dynamic simulations that reflected these user behaviors, with the power consumption of each LED calculated over an eight-hour operating period, allowing for detailed analysis of energy consumption under different occupancy rates. In addition, a sensitivity analysis was performed to examine the effects of fluctuating occupancy times and aisle numbers on the system's energy optimization capabilities. The proposed library lighting system uses LED lights with high and medium light modes. The factors that affect power consumption include the frequency of movement of people in the aisle, the duration of the high light mode (T in seconds, and the power consumption in high light mode (Ph, equal to 15 W). Additionally, we considered the power consumption in medium light mode (Pm, equal to 7 W). To implement the power consumption in MATLAB of one LED, we refer to the calculation methods described in [19], [20] for power consumption. We note that Pled can be expressed as (4).

$$Pled(T) = T \times Ph + (8 \times 3600 - T) \times Pm \quad (4)$$

Therefore, we can conclude that the total power consumption of lighting in the library can be calculated by adding the power consumption of each aisle, with each aisle having a different duration T in high light mode and a different number of LEDs. We have based our research on real data from libraries related to the number of aisles and the approximate duration of the presence of clients in each aisle. Table 1 presents some of the data collected and comparisons between our system and a traditional switch-on/off lighting system.

The results demonstrate that the data from the two initial examples in the table originate from the same library but were collected on different days. The duration of the LEDs in high mode affected the energy savings in our system. Conversely, the results of the second and third examples represent two distinct libraries. Our findings indicate that the number of aisles affects the percentage of energy savings in our system. In contrast, a comparative analysis of our system with a traditional system across twenty distinct scenarios revealed a significant reduction in energy consumption by our lighting system. In response to the insufficient amount of detail about the random forest's ability to predict the importance of aisles, the simulation framework has been expanded to provide a more explicit definition of the procedure used for training and evaluating the model. Specifically, the random forest predictor was generated from a real library user's log of interactions with the aisles where user interactions are described by features such as user V', dwell time before aisle entry (T'), and derived temporal context. Prior to training, the data was subject to a process of feature engineering, whereby continuous values were normalised, and the temporal patterns were discretised to make the model easier to interpret. The dataset was split into two parts, a training set (70%) and a testing set (30%), and a k-fold cross validation method (k =5) was used to enhance the model's robustness and avoid overfitting. Model performance was assessed using standard metrics of classification that quantified model performance. The results provided an overall assessment of the quality of the predictions.

Table 1. Data collected and results of the consumption of energy

Parameters	Scenario 1	Scenario 2	Scenario3
The number of aisle	3	3	5
The number of leds in the aisle	5	5	5
The duration in high light mode	3 h; 2 h; 1 h	4 h; 5 h; 2 h	5.2 h; 1 h; 1.5 h; 2 h; 3 h
The power consumption of our system	24.4 kw	31.2 kw	37.8 kw
The power consumption of traditional system switch (on/off)	29.2 kw	40.5 kw	52.5 kw

The random forest model's inclusion was determined by comparing the model performance against simpler baseline models, the logistic regression systems derived from fixed time-and-speed parameters. The results demonstrated that the random forest model consistently exhibited higher predictive performance and more generalisation ability than any of the simpler baseline classifiers when quantifying how non-linear behaviours affect aisle importance. Hence, the results of the random forest model directly contributed to providing more anticipative lighting control decisions in the simulation, improving both the energy efficiency of the lighting system and user comfort. With potential savings ranging from 23% to 39%. These figures are particularly noteworthy in scenarios where the library is unoccupied, with potential savings reaching 67% of the optimization energy, in scenarios where 50% or more of the aisles are inactive. The results of the simulations confirm the effectiveness of the proposed intelligent lighting system in reducing energy consumption in library environments. By using real-time occupancy data and dynamically adjusting lighting levels, the system achieves significant energy savings, especially compared with traditional on/off lighting controls.

This approach is consistent with previous research [21] that has demonstrated the potential of sensor-based systems in energy management. However, our model goes beyond these studies by introducing a meter and the random forest algorithm tool to analyze the client behavior in the library. The method ensures consistent lighting without unnecessary energy consumption, thereby increasing the accuracy of occupancy-based adjustments. Compared with existing systems, our approach shows improvements in contextual adaptability. Unlike these models, which prioritize either energy efficiency or occupant satisfaction, our system optimally balances both by targeting library environments where aisle-based movement patterns can vary significantly. This dual focus allows our system to provide adequate lighting while conserving energy, especially in low-traffic areas, as evidenced by the comparative data in Table 1.

This stands in contrast to the conventional approach, which often maintains all lighting at maximum brightness, resulting in unnecessary energy consumption, particularly in areas with minimal foot traffic. The principal outcome of our simulations is that the proposed system realizes energy savings of 23% to 39% in comparison to a conventional on/off lighting system. These savings are attributable primarily to the dynamic adjustment of lighting levels, whereby LED transition between high-light and medium-light modes according to the occupancy of the aisles.

Furthermore, the potential for even higher savings [22] (up to 67%) in the absence of foot traffic in the aisles over extended periods underscores the system's efficacy in actual operational settings. The results demonstrate that the duration of the LEDs in high-light mode has a significant effect on the overall power consumption. As illustrated in the initial two examples from the same library, fluctuations in user behavior and aisle occupancy result in disparate energy-saving outcomes. This finding indicates that the efficacy of the system is contingent upon the patterns of human movement [23], which are subject to daily variation. In instances where there is a reduced frequency of movement, the medium-light mode ensures that sufficient illumination is provided without excessive power consumption. The results of our simulations indicate that the number of aisles in a library is a contributing factor to the total energy savings achieved. To illustrate, a comparative analysis of two distinct libraries revealed that an increased number of aisles enhances the potential for energy optimization, as a greater number of zones can be independently managed based on real-time presence. This is especially beneficial in larger libraries, where certain sections may experience minimal to no traffic throughout the day. In such instances, the potential for energy savings is optimized, thereby further substantiating the scalability of the proposed system.

The practical applicability of the system was evaluated by integrating authentic data from libraries concerning aisle utilization. This approach demonstrates the system's adaptability, as it can accommodate diverse layouts and usage patterns, thereby ensuring efficient energy utilization irrespective of the library's size or traffic density. Moreover, the system's design, which prioritizes light quality through matrix-based verification of illumination, ensures that the user experience remains positive despite the reduction in energy consumption [24]. Additionally, the matrix method provides an additional layer of fault detection, allowing for the rapid identification of malfunctioning LEDs and thereby streamlining the maintenance process. While the proposed model demonstrates considerable promise, it is not without limitations. Environmental factors, such as temperature variations or obstacles, have the potential to affect the accuracy of PIR sensors [10], resulting in false occupancy detections. Furthermore, while the simulation employed representative library data, additional empirical testing across multiple library settings with varying layouts would provide greater validation of the system's adaptability [25]. Future research could integrate more advanced sensing technologies, such as thermal or daylight sensors.

4. CONCLUSION

A new intelligent library lighting control approach was proposed and tested in this study. Both the energy-saving tools are also substantively and qualitatively improved via an occupancy-based lighting control system, which varies the light level based on occupancy activity since dynamic occupancy detection provides more significant evidence of appropriate lighting working throughout the necessary range. Simulation results showed that up to an estimated 39% energy could be conserved when developing a library's occupancy-based control system compared to using traditional methods, while traditional efficiency would reach 67% or less where library space is typically under-utilized when occupants leave the check-in area or a section of the building is closed until the library is closed. The new occupancy-based lighting control method of utilizing the counter to register the number of users, as well as each time a counter adds, therefore, allows the lighting system to adjust itself to continue functioning with respect to user numbers when they are there. Furthermore, through the utilization of a newly developed machine learning algorithm, the proposed system may also use the learned user movement patterns of the previous day/week to determine future predictions of user movements while optimizing energy use in the system. The proposed components (e.g., PIR sensors and microcontroller-based lighting control units) support the potential for low-cost hardware for developing the integrated solution. The modular design will accommodate the integration across larger libraries or multiple area/zone applications; however, there may be challenges in terms of providing maintenance for the sensors (e.g., calibration) as well as issues related to the long-term operational reliability of the overall method of integration. Future studies will continue to promote advancements for improving the system intelligence by developing integrated daylight sensors with an adaptable system and increasing system performance efficiency through integrated user preference detection. The proposed occupancy-based lighting controller represents a reasonable and sustainable approach to intelligent library lighting management—and to similar public facilities.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

INFORMED CONSENT

Not applicable. This study did not involve human participants, human data, or any personally identifiable information. All data used were either publicly available, fully anonymized, or derived from non-human sources, and therefore no informed consent was required from individuals.

ETHICAL APPROVAL

Not applicable. This research did not involve human subjects, human biological materials, or experimental procedures on animals. The work was conducted solely on computational models, publicly available datasets, or non-sensitive data that did not require intervention with living organisms. Therefore, ethical approval from an institutional review board or animal ethics committee was not necessary for this study.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article.

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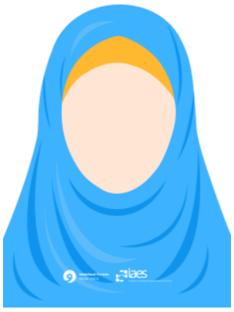

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