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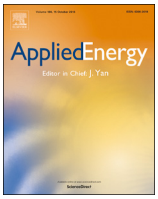

Energy-maintenance optimization for retrofitted lighting system incorporating luminous flux degradation to enhance visual comfort

Alice Ikuzwe*, Xianming Ye, Xiaohua Xia

Center of New Energy Systems, Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria 0002, South Africa

HIGHLIGHTS

- Lighting control system with occupancy and light sensors to adjust LED illuminance.
- Luminous flux degradation model based on users' lighting level requirements.
- Energy-maintenance optimization model based on luminous flux degradation.
- The model indicates the number of lamps to be replaced instead total replacement.
- The model optimizes simultaneously maintenance costs and energy savings.

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ABSTRACT

Retrofitting existing buildings with energy-efficient lighting systems is an effective way to reduce their lighting energy consumption and improve lighting quality. In a lighting system, the illumination level decreases over time owing to the luminous flux degradation of lights. This degradation may cause visual discomfort if proper maintenance is not carried out. Also, energy savings decrease with the degradation of retrofitted lights. Maintenance of lighting devices requires investments for the purchase and installation of new lamps. Therefore, optimum balance is required between maintenance costs and the performance of the lighting system. This study presents an energy-maintenance optimization model, which takes into account the luminous flux degradation. Luminous flux degradation is modeled based on users' lighting level requirements. Based on the proposed luminous flux degradation model, the energy-maintenance optimization model is formulated to find the optimal number of lamps to be replaced, maintenance schedules, and brightness dimming level, while taking into account users' lighting level requirements, maintenance budget, and energy savings. An open-plan office is taken as a case study to illustrate the effectiveness of the proposed optimal energy-maintenance plan. It is found that the optimal energy-maintenance plan yields to 31.27 MWh energy savings in 10 years. Compared to the full maintenance, the optimal maintenance plan developed in this study reduces the total maintenance cost by 30%.

1. Introduction

Lights are ranked among the largest consumers of electricity in schools, offices, and commercial buildings [1]. According to a report [2] from the South African Department of Energy, lighting accounts for up to 21% of the total electricity consumed in commercial buildings and 26% of the total electricity used in schools in South Africa. Electricity used in buildings is mainly supplied by coal-fired power stations [3], which makes them responsible for the largest share of the country's carbon dioxide emissions [4]. Consequently, minimizing electricity used for lighting can be one of the ways to reduce overall building energy consumption and related greenhouse gas emissions.

Artificial lighting energy use can be reduced using two main approaches [5]: a conservation approach and an efficiency approach. The conservation approach reduces the time of use of lights and may include behavioral change, building design, and automation [6]. The efficiency approach reduces lighting energy usage, generally using more efficient lighting technology. Currently, light-emitting diodes (LEDs) are the most energy-efficient source of electricity available on the market. Energy efficiency combined with long operating life and reliability makes LEDs a potential choice for the next generation of lighting systems including automotive, emergency, back-light, indoor, and outdoor lighting [7]. Energy consumption is not the only issue to consider when designing an energy-efficient lighting system; visual comfort is also

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[*] Corresponding author.
E-mail address: kanoni.alice@gmail.com (A. Ikuzwe).

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important.

Visual comfort is the subjective reaction to the quantity and quality of light in a given space. The lighting quantity is a measure of how much light one has at the workspace or in the room, and the quality of light is generally analysed using factors such as glare, light uniformity, and color rendition. The impacts of glare, light uniformity, and color rendering are linked to the light level [8]. Glare is caused by excessive and uncontrolled brightness of the light source. Light uniformity is the ratio of the level of illumination required for the task that will be carried out to the available illumination level. Both light level and color rendering play a critical role in color perception. At a low light level, good color rendition is difficult regardless of the light source used. For visual comfort, the Illuminating Engineering Society (IES) has developed light level recommendations for a wide range of tasks. For computer workstations, a minimum light level of 300 lux and a maximum light level of 500 lux are recommended for visual comfort [9]. An inadequate illuminance level (less than the recommended threshold level) can cause low task visibility, which results in visual discomfort. Task visibility is crucial in offices because of the intense concentration that is required of office workers, and because they typically do their work in front of computer screens.

Maintenance refers to a combination of all actions (e.g., cleaning, repairs, and replacement, etc.) intended to improve system efficiency and guarantee safety during operation. Those actions may be performed regularly to maintain the equipment in an acceptable operational condition (preventive maintenance) or can be done to identify and correct a defect so that the failed equipment can be restored to an operational condition (corrective maintenance) [10]. Various studies have been done concerning single-unit system [11,12], and multi-unit system maintenance [13,14]. Studies taking into account maintenance of lighting systems are scarcer. In reported literature on lighting maintenance, periodic preventive maintenance based on replacing failed lamps at a certain maintenance level is the most often applied. For instance, Wang and Xia [15] proposed a multistate-based control system approach for maintenance plan optimization, taking into account corrective maintenance of lighting and preventive maintenance of heating, ventilation, and air-conditioning. References [16,17] formulated a maintenance plan of an energy-efficient lighting retrofit project. The lighting maintenance plan developed in the aforementioned studies focused on burnout failure. However, before lamps burn out, their luminous flux gradually decreases over time. This means before lamps burn out, the illumination level may be inadequate to carry out a task safely, which may lead to visual discomfort. In this study, a lighting maintenance plan that takes into account luminous flux degradation is formulated.

To design a proper maintenance plan for the lighting system, it is necessary to model the lighting failure. The light failure models in existing studies can be classified into two main categories: burnout failure models and lumen degradation models. Studies [18,19] discussed the light failure and population decay models of compact fluorescent lamps based on burnout failure. Reference [20] proposed a hybrid method that combines thermal modeling and temperature measurement to predict the luminous flux degradation of LED lamps. Reference [21] developed an accelerated test method for luminous flux degradation to reduce the test time within 2000 h at elevated temperatures. The Illuminating Engineering Society (IES) of North America released the TM-21 standard in 2011 [22] to predict the lumen maintenance life of LED lights based on collected lumen maintenance data from the IES LM-80 test report [23]. Existing studies have revealed that the primary causes of luminous flux degradation of LEDs are the driving current and operating junction temperature. However, the LED degradation models presented in the literature are usually performed under several specific conditions including constant driving current and temperature, while the driving current depends on the user profiles and driving schemes [24]. In this study, the luminous flux degradation of LEDs is modeled based on the variation of the operating junction temperature owing to the users' lighting level requirements.

The main contribution of this study is the formulation of the luminous flux degradation model that takes into account the users' lighting level requirements, and the energy-maintenance optimization model that takes into account the luminous flux degradation. In the previous lighting maintenance optimization problems, luminous flux degradation was neglected. However, the aspect of human well-being, such as state of mind or level of fatigue is affected by illumination deficiencies. Workers who suffer the effects of illumination deficiencies constantly can suffer from eye fatigue and functional disorders, even if in many cases they are not aware of it. The main advantage of the maintenance plan developed in this study is that luminous flux degradation is monitored and users' lighting level requirements are maintained at a constant level.

In this study, an energy-maintenance problem of a lighting system, which takes into account luminous flux degradation, is formulated into an optimization problem maximizing energy savings and minimizing maintenance costs. A multi-objective optimization model is formulated to find the optimal number of lamps to be replaced, maintenance schedules, and lamps' brightness dimming levels. The number of lamps to be replaced and lamps' brightness dimming level are chosen as the problem design variables to maintain lighting levels and optimize energy savings and maintenance costs. The design variables are optimally decided based on light levels required by users, energy savings, and maintenance budget limits. An existing academic office is selected to demonstrate the effectiveness of the proposed model. The study is evaluated over 10 years with a sampling interval of one month.

The organization of the paper is as follows: Section 2 presents the problem formulation and LED luminous flux degradation modeling. Section 3 presents the optimization problem formulation. Section 4 presents the case study. Simulation results are discussed in Section 5, followed by conclusions in Section 6.

2. Problem formulation and modeling

We consider an LED lighting system in a typical open-plan office as depicted in Fig. 1. We divided the office into different zones with an equal number of light sources in each zone. In each zone, light sensors are available to monitor the real-time artificial light output, and the users can adjust the lighting output to their preferred lighting levels by using the light dimming controllers. The average illuminance in each zone is measured in the center of the zone at the height of the desk, 0.76 m from the floor. Initially, the lighting system is slightly oversized to maintain the required light level over the lifetime of the installation. When the LED lighting system is new, users have to dim the lights to their preferred illuminance levels. However, the LEDs' luminous flux degrades as time goes by, hence users have to stretch the LEDs' performance to meet the set illuminance levels. However, the LEDs cannot satisfy the users' preferred illuminance levels even they are working at 100% brightness level. This phenomenon is usually overlooked as those LEDs with significant luminous flux degradations still have light output instead of burnout. When users working under the degraded LEDs over a long time, they are experiencing visual discomfort. To satisfy the users' lighting level requirements and ensure their visual comfort, those LEDs with significant performance degradations must be replaced. In practice, the replacement of lighting devices implies extra investment. This study aims to develop an optimal maintenance plan that optimizes both lighting system performance and maintenance costs whilst satisfying users' lighting level requirements. To characterize the optimal LED lighting maintenance plan, we can formulate the problem into an optimization problem. Our formulation starts with the modeling of luminous flux degradation.

Luminous flux degradation is the natural decrease in light output that occurs as a lamp operates over time. Different from traditional lights that will burn out at the end of their life span, the LEDs' effective lifetime is estimated based on the level of their luminous flux

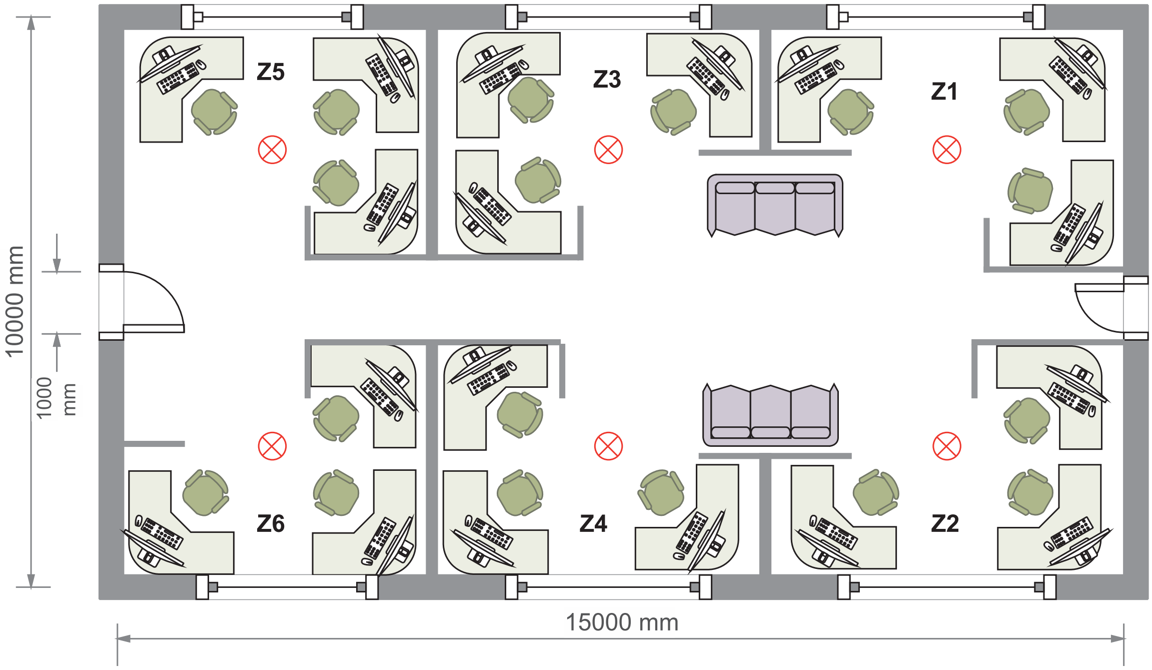

Fig. 1. Layout of the office under study.

degradation. The luminous flux degradation can be accelerated or decelerated by varying operating conditions such as an elevated temperature. The existing luminous flux degradation models are mostly based on some specific current levels. However, driving current may vary depending on users' lighting level requirements. In this study, luminous flux degradation of LEDs is modeled based on users' lighting level requirements.

In Fig. 1, LEDs in each zone are controlled by one dimming controller to satisfy users' lighting level preference. Let $d_i(j)$ denote the dimming level of lamps in zone i at time j, $d_i(j) \in [0, 1]$, and $d_i(j) = 1$ for full brightness, and $d_i(j) = 0$ when lamps are off, $i = 1, 2, \cdots Z, j = 1, 2, \cdots, K$. The illuminance level in each zone is properly set according to the users' lighting level preference. In this study, $E_{set,i}$ denotes the set illuminance in zone i, which is considered constant. The measured illuminance by the light sensor in each zone is denoted by $E_i(j)$.

Daylight and light from neighboring zones are not considered. They are important factors to consider when luminous flux control is concerned, but the objective of this paper is maintenance planning by modeling luminous flux degradation. This modeling process does not necessarily have to consider daylight and neighboring lights, because lumen output data can be obtained without daylight and neighboring lights, for example at night, in the laboratory, and isolation of the light concerned.

There are two main methods of calculating illuminance level: lumen method and point-by-point method [25]. The point-by-point method is used to determine illuminance at any point on a surface or workplace while the lumen method is used to calculate the average illuminance on a workplace within a space. In this study, the lumen method is used instead of the point-by-point method because it gives more accuracy for indoor applications as it takes into consideration the allowance for light distribution of luminaire and room surface, and the allowance for light output reduction due to deterioration and dirt, while the accuracy of point-by-point method is negatively influenced by the office partitions.

By using the lumen method, the measured illuminance in zone i can be calculated as

$$E_i(j) = \frac{n \times \phi_i(j) \times d_i(j) \times U_f \times M_f}{A}, \tag{1}$$

where n is the number of lamps installed in each zone, $\phi_i(j)$ is the luminous flux of each lamp in the zone i at time j, U_f is the utilization factor (allowance for light distribution of luminaire and room surface), M_f is the maintenance factor (allowance for light output reduction due to deterioration and dirt), and A is the surface area (m^2) of each zone. $\phi_i(j)$ is estimated using the exponential decay model (2). Previous studies [26,27] analyzed different degradation models of LEDs and recommended the exponential decay model as an appropriate empirical model to describe the lumen degradation of LEDs.

$$\phi_i(j) = \phi_0 e^{-\beta_i(j)t_j}, \tag{2}$$

where ϕ_0 is the initial lumen output of new LEDs (lm), t_j is the cumulative operating hours (h), and $\beta_i(j)$ is the degradation rate of the LEDs in zone i at time j.

The LED degradation rate $\beta_i(j)$ changes when the junction temperature changes. The relationship between the LED degradation rate and the operating junction temperature can be expressed by the Arrhenius equation as [21]

$$\beta_i(j) = ae^{\left(\frac{-E_{act}}{k_b T_{m,i}(j)}\right)}, \tag{3}$$

where a is the Arrhenius pre-exponential factor, k_b is the Boltzmann constant (8.617385×10^{-5} eV/K), E_{act} is the activation energy (eV), and $T_{m,i}$ is the LED junction temperature (K). $T_{m,i}$ is a function of the LEDs' driving current. From the electro-thermal model [24], $T_{m,i}$ can be expressed as

$$T_{m,i}(j) = T_a + P_{heat,i}(j) \times R_{th}, \tag{4}$$

where T_a is the ambient temperature (K), $P_{heat,i}(j)$ is the electricity converted into heat (W) as in (5), and R_{th} is the thermal resistance (K/W). In this study, the thermal resistance is obtained from the LED manufacturer sheet.

$$P_{heat,i}(j) = k_h \times I_F \times V_F \times d_i(j), \tag{5}$$

where I_F and V_F are the driving current and forward voltage, respectively, and k_h is the heat coefficient.

3. Optimization problem formulation

The energy-maintenance optimization problem is formulated to maximize energy savings and minimize the maintenance cost while taking into account luminous flux degradation. The model optimally determines the dimming levels and the number of lamps to be replaced at each evaluating interval. The optimization problem is described in the following subsections.

3.1. Design variables

The design variables of the energy-maintenance optimization problem are the dimming levels and number of lamps to be replaced. Let $d_i(j)$ denote the dimming level of lamps located in zone i at time j and $m_i(j)$ the number of lamps to be replaced in zone i at time j. $d_i = [d_i(1), d_i(2), \cdots, d_i(K)]$, and $m_i = [m_i(1), m_i(2), \cdots, m_i(K)]$. $D = [d_1, d_2, \cdots, d_Z]$, and $M = [m_1, m_2, \cdots, m_Z]$. The decision variable of the optimization problem is given as

$$X = [D, M]^T. \tag{6}$$

3.2. Objective function

The energy-maintenance optimization problem has two objectives: maximizing energy savings (ES) and minimizing maintenance costs (C_m). The weighted sum method [28] is employed to translate the multi-objective optimization problem into a single-objective optimization problem as

$$\min \quad J = -w_1 ES + w_2 C_m, \tag{7}$$

where w_1 and w_2 are the weighting coefficients, which are in the range $[0, 1]$, and $w_1 + w_2 = 1$. Weighting coefficients are selected depending on the project developer's preference. The higher the weighting coefficient, the more preference is given to the attached objective.

The maximum values of energy savings ($\overline{ES}$) and maintenance cost ($\overline{C}_m$) are used to normalize the objective function (7).

$$\min \quad J = -w_1 \frac{ES}{\overline{ES}} + w_2 \frac{C_m}{\overline{C}_m}. \tag{8}$$

The ES is the difference between lighting energy consumption before and after the installation of lighting controls

$$ES = EC_B - EC_A, \tag{9}$$

where EC_B is the lighting energy consumption (kWh) before the installation of lighting controls and EC_A is the lighting energy consumption (kWh) after installation.

$$EC_B = Pr \times n \times Z \times t_{s,b} \times K, \tag{10}$$

$$EC_A = \sum_{i=1}^{Z} \sum_{j=1}^{K} Pr \times n \times d_i(j) \times t_{s,i}, \tag{11}$$

where Pr is the rated power (kW) of each lamp, Z is the total number of zones, $t_{s,b}$ represents the fixed operating hours before the installation of lighting control system in each sampling interval, and $t_{s,i}$ represents the controlled operating hours in each sampling interval in zone i.

The maintenance cost $C_m$of all zones over the evaluation period is given as:

$$C_m = \sum_{i=1}^{Z} \sum_{j=1}^{K} \left(\alpha + L_c\right) \times m_i(j), \tag{12}$$

where α is the unit price (R[1]) of each lamp and L_c is the labor cost to replace a lamp.

3.3. Constraints

i. Boundary constraint

$$\begin{cases} 0 \leqslant d_i(j) \leqslant 1, \\ 0 \leqslant m_i(j) \leqslant n. \end{cases} \tag{13}$$

Constraint (13) indicates that the dimming levels are continuous values bounded between 0 (off) and 1 (full brightness), and the number of lamps to be replaced are integer values bounded between 0 (no replacement) and n (full replacement).

ii. Illuminance level

The average measured illuminance in the zones should be equal to the users' set illuminance. The low (300 lux) and high (500 lux) threshold acceptable light levels for computer workstations are considered for users' set illuminance levels.

$$E_i(j) = E_{set,i}. \tag{14}$$

Eq. (1) can also be expressed as

$$E_i(j) = \frac{\Theta_i(j) \times d_i(j) \times U_f \times M_f}{A}, \tag{15}$$

where $\Theta_i(j)$ is the total luminous flux (lm) of lamps in zone i at time j.

$$\Theta_i\left(j+1\right) = \sum_{l=1}^{L} \phi_i^l(j) e^{-\beta_i(T_{m,i}(j)) t_{s,i}} + m_i(j)\phi_0 e^{-\beta_i(T_{m,i}(j)) t_{s,i}}, \tag{16}$$

where $L = n - m_i(j)$, and $\phi_i^l(j)$ is the luminous flux of non-replaced lamps l at time (j). $\phi_i^l(j)$ is calculated using Eq. (2).

iii. Maintenance budget limit

The maintenance budget limit constraint (17) indicates that the expenses for maintenance at time j should not exceed the cumulative available profit.

$$\left(\alpha + L_c\right) \times m_i(j) - \sum_{k=1}^{j} ES_i(k) \times ET \leqslant 0, \tag{17}$$

where ET is the electricity tariff (R/kWh) from Eskom (a South African electricity public utility), which is considered constant during each sampling interval.

iv. Energy savings constraint

The energy savings constraint (18) indicates that the energy savings of each zone at each sampling interval should be greater than or equal to the targeted amount of energy savings.

$$ES_i(j) \geqslant \Phi, \tag{18}$$

where Φ is the targeted amount of energy savings, which is usually the percentage of energy consumption before retrofitting.

3.4. Solution methodology

The energy-maintenance optimization problem (6)–(18) is formulated as a mixed-integer program and is solved using the Solving Constraint Integer Program (SCIP) available in the MATLAB interface OPTI toolbox[2]. SCIP is currently one of the fastest non-commercial solvers for mixed-integer programming. It is also a framework for constraint integer programming and branch-cut-price[3]. It uses the Interior Point Optimizer (IPOPT) algorithm. IPOPT is an open-source

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[1] Rand(R): South African currency (1 Rand = 0.070 USD), as on 04 July 2019

[2] https://www.inverseproblem.co.nz/OPTI/index.php/Solvers/SCIP

[3] http://scip.zib.de/

application for large-scale linear and nonlinear programs; it implements a primal-dual interior method and uses line searches based on filter methods [29]. The solver offers a solution to problems of the form:

$$\min f(X),$$

$$\text{subjectto: }\begin{cases} AX \leqslant b \quad \text{inequality linear constraint,} \\ A_{eq}X = b_{eq} \quad \text{equality linear} \\ \text{constraint,} \\ C(X) \leqslant d \quad \text{inequality nonlinear constraint,} \\ C_{eq}(X) = d_{eq} \quad \text{equality nonlinear constraint,} \\ l_b \leqslant X \leqslant u_b \quad \text{variables bounds,} \\ x_i \in \mathbb{Z}, \\ x_i \in 0,\ 1. \end{cases}$$

4. Case study

A lighting system in an open-plan office of length 15 m, width 10 m, and height 2.8 m at the University of Pretoria (UP) were considered as the case study. The office is divided into six zones (Z1, Z2, Z3, Z4, Z5, and Z6), as shown in Fig. 1. Z1 and Z4 (zones for senior researchers) are occupied 12 h/day, Z2 and Z5 (zones for post-graduate students) are occupied 10 h/day, and Z3 and Z6 (zones for under-graduate students) are occupied 7 h/day. Users' set illuminance level in Z1, Z2, and Z3 is 300 lux, and 500 lux in Z4, Z5, and Z6. LED lighting system installed in this office is composed of 36 Philips LED tubes of 1200 mm, 20 W, 4000 K, and 2650 lm each. Each zone is equipped with six LED tubes. The LED tubes are placed in rectangular troffers with two LED tubes per fixture (three fixtures/zone). A lighting control system, equipped with light sensors to adjust artificial light to the light level required by users and occupancy sensors to detect the present of users in the zones, is installed in this office. To avoid false triggers in the lighting system, occupancy sensors are equipped with time delay.

5. Results analysis

This section presents simulation results of the case study in Section 4 under four scenarios: 1) baseline; 2) lighting control system is not considered and maintenance is carried out according to IES LM-80-08 standard of LEDs failure; 3) lighting control system is applied with full maintenance; and 4) lighting control system is applied with optimal maintenance plan.

The data used in the simulations to validate the formulated models are presented in Table 1. The LED lights parameters (k_b, k_h and R_{th}) are obtained from Philips manufacturing data sheet, LED lighting system design parameters (U_f and M_f) are obtained from the reference [25] and n is calculated using the lumen method, the A of the zones is measured using a measuring tape, the characteristics of the LED lights (Pr and ϕ_0) are measured using integrating sphere in the lab, operating hours ($t_{s,1}$, $t_{s,2}$, $t_{s,3}$, $t_{s,4}$, $t_{s,5}$, $t_{s,6}$, and $t_{s,b}$) are obtained from a monitoring survey conducted, and parameters (Φ, w_1, and w_2) are chosen based on the project developer's preferences.

Table 1
Simulation parameters.

Parameter	Value	Unit	Parameter	Value	Unit
k_b	8.617385×10^{-5}	eV/ K	$t_{s,1} = t_{s,4}$	264	h
k_h	0.75		$t_{s,2} = t_{s,5}$	220	h
R_{th}	2	°C/W	$t_{s,3} = t_{s,6}$	154	h
U_f	0.9		$t_{s,b}$	528	h
M_f	0.9		Φ	$0.3EC_B$	kWh
n	6		w_1	0.5	
A	22.5	m^2	w_2	0.5	
Z	6		L_c	10	R
Pr	20	W	α	170	R
ϕ_0	2650	lm	ET	0.95	R

5.1. Scenario 1

In this scenario, the LED lighting system is installed without any lighting control system or maintenance plan. Lamps in all zones operate at their full brightness the whole day. Lighting energy consumption per month is 380.16 kWh, and 45.61 MWh over the evaluation period. Lighting energy cost over the evaluation period is R 43,338. Luminous flux of LEDs and illuminance levels in all zones over time are shown in Fig. 2. It is observed that the illuminance level in zones decreases with the degradation of luminous flux. The illuminance level in the zones decreases from 570 lux in the first month of operation to 343 lux at the end of the evaluation period.

5.2. Scenario 2

In this scenario, there is no lighting control system, but maintenance is scheduled following the IES LM-80-08 standard of LEDs failure. According to this standard, LED lights are declared failed if the lumen output is less than 70 % (lumen threshold) of the initial lumen output. All lamps operate at their full brightness at each sampling interval, and the operating junction temperature and degradation rate are considered constant over the evaluation period. By using Eq. (2), the time required for lamps to reach the lumen threshold is estimated. Results show that the lumen output of lamps will reach the lumen threshold after operating 84 months, thereafter all lamps will be replaced by new ones. As shown in Fig. 3, the illuminance level in zones decreases with time and increases when maintenance is performed. The maintenance cost over the evaluation period is R 6,480. Lighting energy consumption and energy cost over the evaluation period are 45.61 MWh and R 43,338, respectively.

5.3. Scenario 3

In this scenario, we consider the lighting control system together with full maintenance. Light and occupancy sensors adjust artificial light to the light level required by users and detect the presence of users in the zones, respectively. Light sensors measure the average illuminance in the zones at the desk level. The measured illuminance is compared to the users' set illuminance; if the measured illuminance is higher than the users' set illuminance, lamps are dimmed to meet users' lighting preference, when the measured illuminance is less than the users' set illuminance, all lamps in the zone are replaced by new ones. The dimming level in each zone at each sampling interval is used to estimate the operating junction temperature, thereafter the degradation rate and luminous flux are calculated. Results show that there will be no replacement in Z1, Z2, and Z3 over the evaluation period. Luminous flux in these zones degrades over time, but still meets the users' set illuminance level. Lamps in Z4 will be replaced every 44 months, in Z5 lamps will be replaced every 56 months, and in Z6 lamps will be replaced every 68 months. Fig. 4 shows energy savings in each zone over time. Initially, the lighting system is usually slightly oversized to maintain the required light level over the lifetime of the installation. This is mostly due to lighting design factors such as maintenance factor (M_f) and utilization factor (U_f). The factors M_f and U_f tell you how much you need to increase the light level at the start to maintain the required light level over the lifetime of the installation. Thus, more energy is saved at the beginning of the installation when dimming control is installed and decreases with time due to the light output degradation since the dimming levels will decrease to maintain the required light levels. Energy savings over the evaluation period in Z1, Z2, Z3, Z4, Z5, and Z6 are 5.5 MWh, 5.97 MWh, 6.54 MWh, 4.13 MWh, 4.6 MWh, and 5.2 MWh, respectively. The total energy savings and maintenance costs over the evaluation period are 31.94 MWh and R 5,400, respectively.

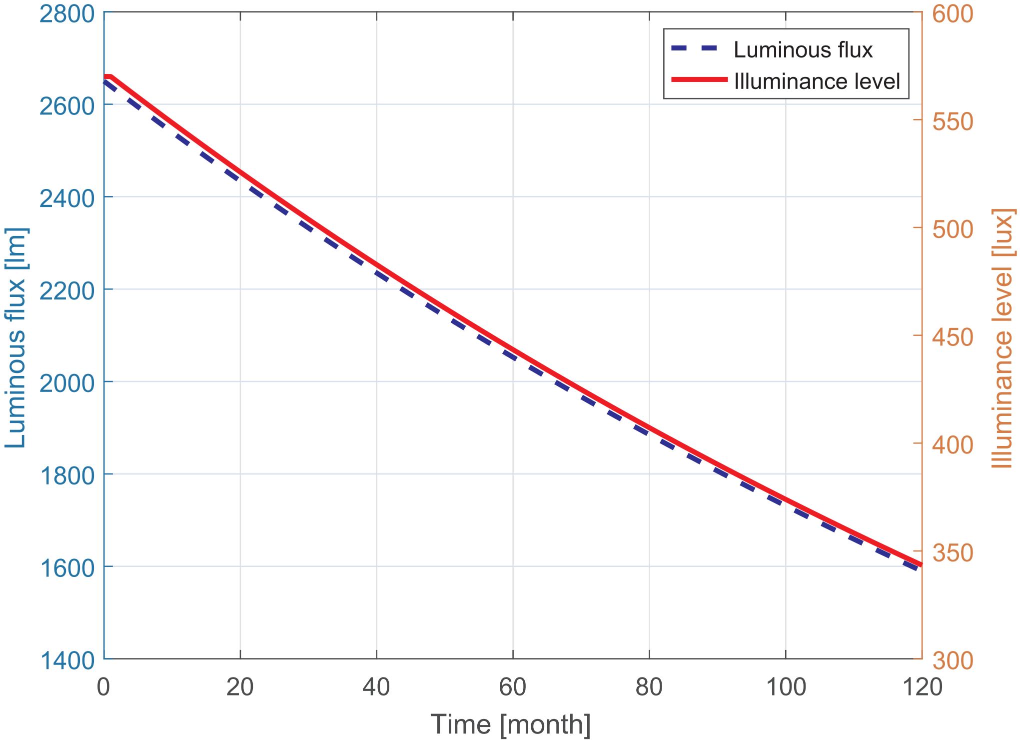

Fig. 2. Luminous flux and illuminance level degradation over time in Scenario 1.

5.4. *Scenario 4*

In this scenario, lighting controls and optimal maintenance are considered with the aim of maximizing energy savings and minimizing maintenance costs. The optimal maintenance plan aims at finding the optimal number of lamps to be replaced, and the dimming level in each zone at each sampling interval to maintain energy savings and satisfy users' lighting level requirements. With this model, it is possible to estimate when each zone will be maintained, how many times, and how many lamps to be replaced during maintenance.

Results show that there will be no maintenance in Z1, Z2, and Z3. Luminous flux in these zones degrades over time, but still meets the users' set illuminance level. Fig. 5 shows the maintenance schedule and the optimal number of lamps to be replaced in Z4, Z5, and Z6. Z4 and

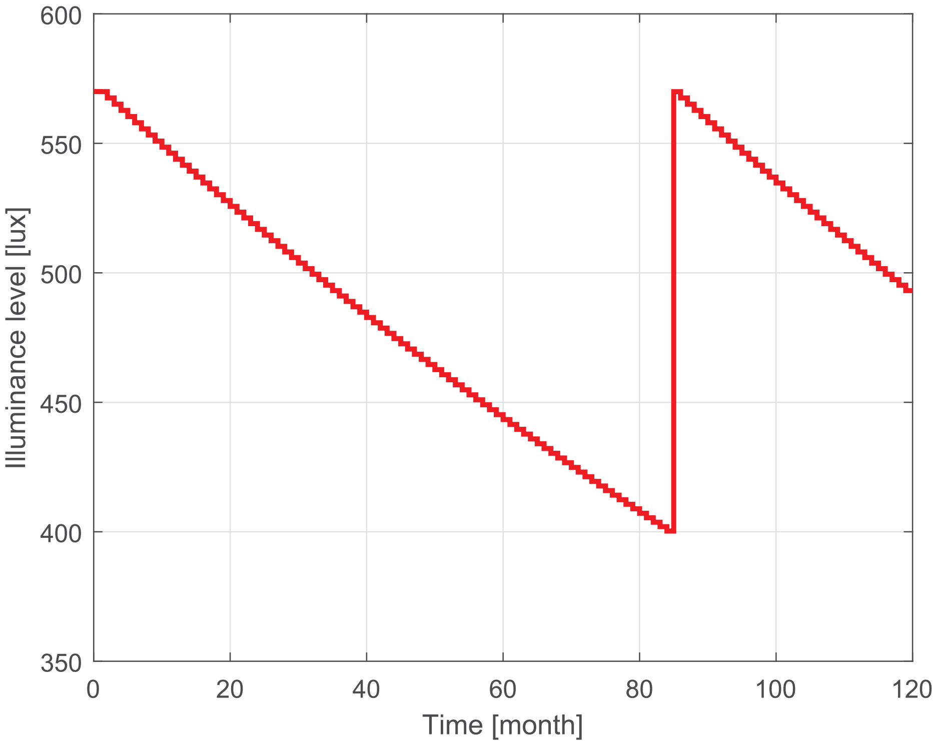

Fig. 3. Illuminance level in zones in Scenario 2.

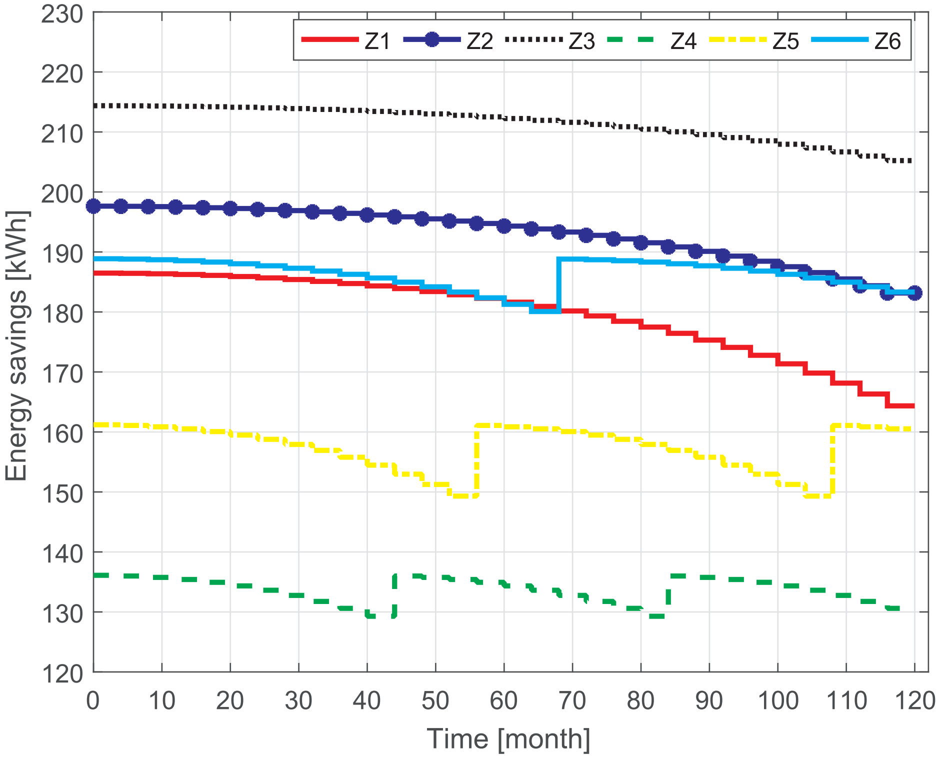

Fig. 4. Energy savings in each zone under Scenario 3.

Z5 will be maintained three times and Z6 will be maintained twice over the evaluation period. Energy savings and maintenance cost are treated equally in this study, thus the weighting coefficients in the objective function are equal, i.e. $w_1 = w_2 = 0.5$. However, it is observed that the optimal number of replaced lamps and dimming levels in each zone during each maintenance interval may vary with weighting coefficients. For example, for $w_1 = 0.5$, and $w_2 = 0.5$, 21 lamps will be replaced over the evaluation period, while for $w_1 = 0.7$, and $w_2 = 0.3$, 24 lamps will be replaced. The impact of users' set illuminance level on the optimal number of lamps to be replaced is analyzed by varying the users' set

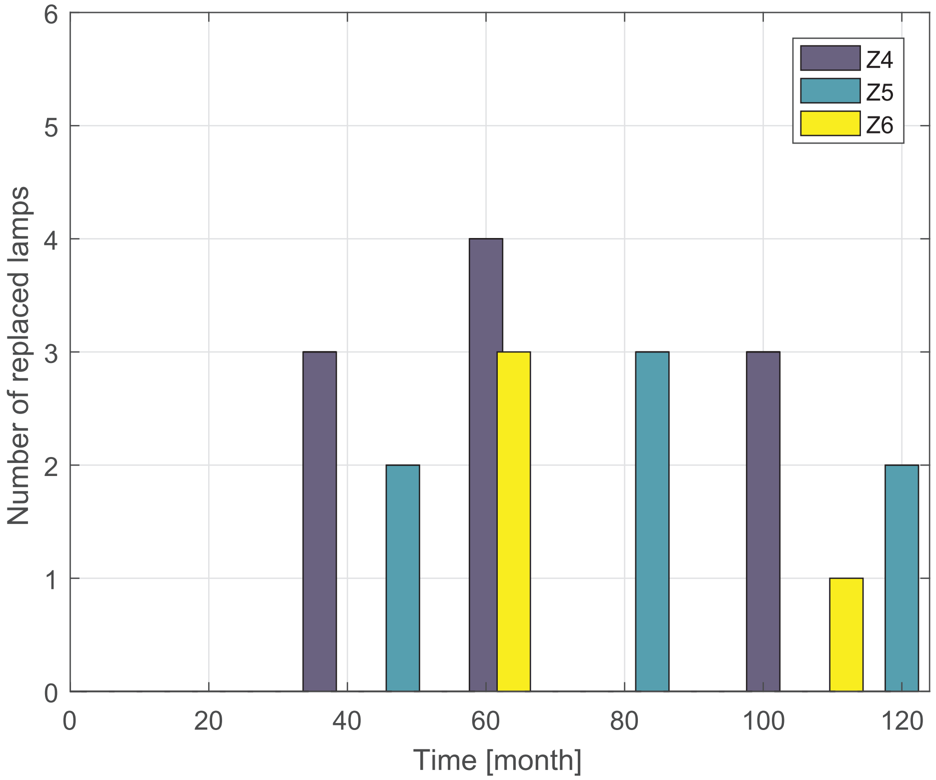

Fig. 5. Optimal number of replaced lamps under Scenario 4.

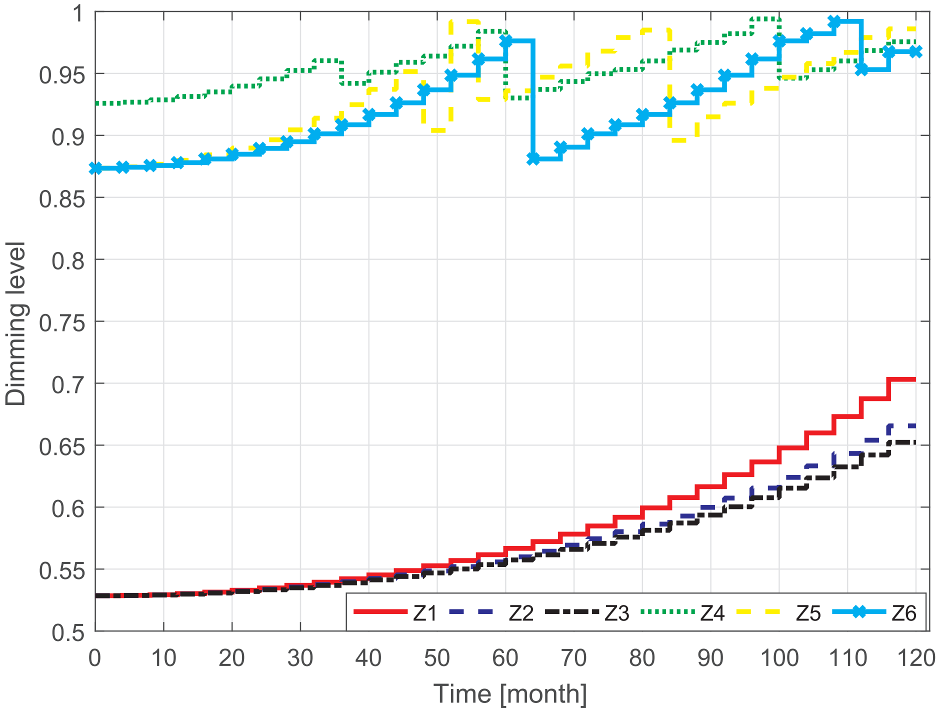

Fig. 6. Dimming level in each zone under Scenario 4.

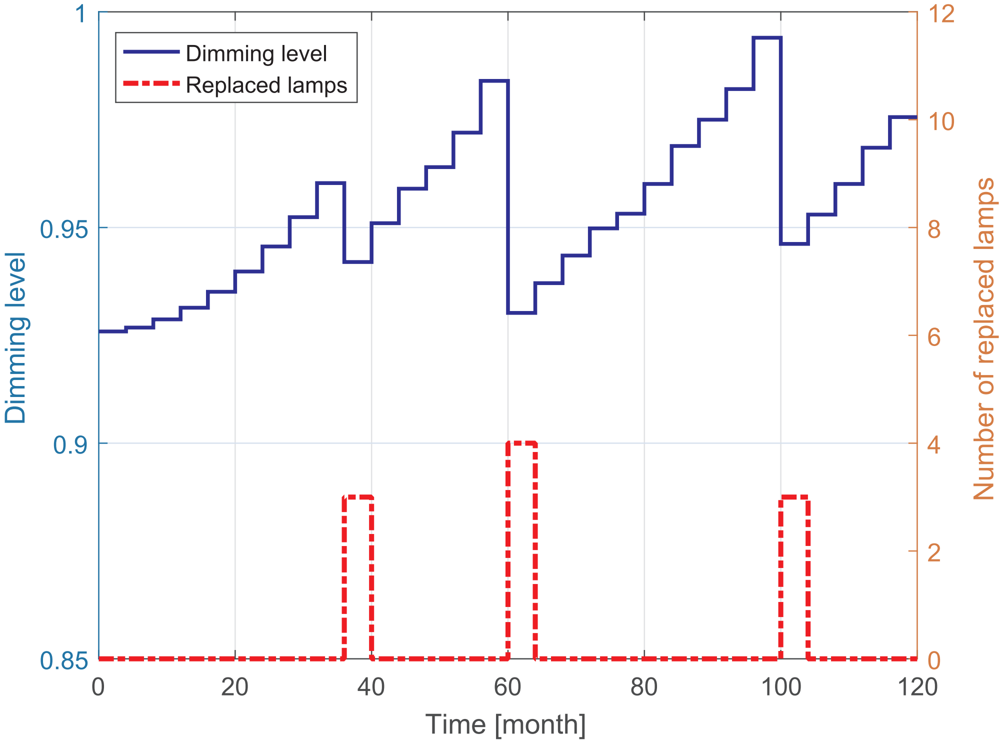

Fig. 7. Dimming level and number of lamps replaced in Z4 under Scenario 4.

illuminance level to 350 lux, 400 lux, and 450 lux in Z2 and Z6. Results show that the number of replacements decreases when the users' set illuminance level decreases and increases when the users' set illuminance level increases. For example the number of replacements increases to 2, 3, and 4 in Z2 when illuminance level is set to 350 lux, 400 lux, and 450 lux, respectively, and decreases to 3, 1, and 0 in Z6 when illuminance level is set to 450 lux, 400 lux, and 350 lux, respectively. Fig. 6 presents the dimming levels in each zone. Dimming levels and number of replacements are shown in Fig. 7. It is observed that dimming levels decrease over time owing to luminous flux degradation and increase when lamps are replaced. Results show that 31.27 MWh of the lighting energy consumption can be saved in this scenario. The maintenance cost over the evaluation period is R 3,780.

Table 2
Project key performance factors analysis over the evaluation period.

Performance factor	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Energy consumption (MWh)	45.61	45.61	13.67	14.34
Energy savings (MWh)	0	0	31.94	31.27
Maintenance cost (R)	0	6,480	5,400	3,780
Energy cost (R)	43,338	43,338	12,987	13,623
Total cost	**R 43,338**	**R 49,818**	**R 18,387**	**R 17,403**

5.5. Discussion

Scenarios 1 and 2 do not reduce lighting energy consumption, but compared to Scenario 1, Scenario 2 improves lighting quality because lamps are replaced once their light output has reached the lumen threshold. Energy savings achieved in Scenario 3 and Scenario 4, are obtained from installing light and occupancy sensors, and maintenance (lamp replacements). The energy consumption increases when luminous flux degrades since the dimming levels will decrease to maintain the users' set illuminance levels. Scenario 3 produces more energy savings than Scenario 4 because more failed lamps are replaced in Scenario 3. Scenario 3 was found to save 0.67 MWh more than Scenario 4. Compared to the full maintenance plan applied in Scenario 3, the optimal maintenance plan developed in Scenario 4 reduces maintenance cost by 30%. Table 2 presents and compares the energy consumption, energy savings, and maintenance cost under scenarios 1,2,3, and 4.

The installation of light and occupancy sensors not only contributes to the reduction of energy consumption but also contributes to the implementation of an effective maintenance plan and visual comfort. However, the installation of light and occupancy sensors requires additional investments for the purchase and installation of these. This can be a challenge for the implementation of lighting controls.

Although the energy-maintenance optimization model formulated in this study can be applied to other lighting projects, caution is required in the following aspects. In this study, the Philips LED tubes are considered in an open-plan office. Different energy-efficient lighting retrofit projects may contain different types of energy-efficient lights, which may affect the maintenance plan.

6. Conclusion

An energy-maintenance optimization for an energy-efficient lighting system is studied. The purpose of this study is to minimize lighting energy consumption and improve lighting quality in existing buildings. The present model introduces the luminous flux degradation of light-emitting diodes lights. Luminous flux degradation is considered to keep users' lighting requirements constant and estimate energy savings accurately. In the optimization approach, an optimal maintenance plan is formulated to maximize energy savings and minimize maintenance costs based on the proposed luminous flux degradation model. A case study carried out shows that in 10 years, the formulated optimal energy-maintenance plan would achieve 31.27 MWh energy savings with maintenance costs of R3,780. Compared to the full maintenance, the optimal maintenance plan developed in this study reduces the total maintenance cost by 30%. This optimization model can be used by the building managers/owners to predict when maintenance should be performed and how many lights can be replaced. Based on the simulation results, it is concluded that effective maintenance should be planned to keep users' light level requirements constant and maintain the savings of retrofitted lighting system. It is noted that the optimal maintenance plan is more cost-effective than full maintenance. Further improvement of this study could include other energy-efficient lighting technologies and a large population.

Declaration of Competing Interest

The 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.

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