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Research article

Optimisation of LED luminaires renewal interval based on proposed CLO adjustment method☆

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A B S T R A C T

A considerable part of electrical power is consumed in lighting systems. Electrical power usage and, as a result, generation is proportional to CO_2 emissions. CO_2 emissions result in climate change. Many countries encouraged people to use modern light sources, including LEDs, to increase the efficiency of lighting systems. An LED, during its long life, is subjected to gradual degradation. Its degradation can be understood from its radiant flux decrement. Some standards, including LM 80-08, addressed this issue. Constant lumen output (CLO) drivers are used to deal with LED degradation issues. There is not much scientific research on the topic of CLO. This paper suggests a scientific approach to finding CLO's exact output voltage as a function of time during the LED lifetime, limiting energy consumption to the required value. Also, a method for finding the best time to replace LED luminaires to minimise the financial burden for the owners has been found. By optimising renewal time for LED luminaires, energy usage (CO_2 emission) and end-of-life waste will be managed to the required value. In addition, for use in CLOs, the paper suggests adding more specified data to the LM 80-08 report.

1. Introduction

1.1. LEDs as means of reducing CO_2 emissions

Climate change has become an essential global issue in the last decades. Global warming as a consequence of climate change is a big problem worldwide. Rising sea levels in coastal lines have threatened essential ports and harbours in the most important commercial zones worldwide due to polar ice melting, which is a consequence of global warming. Measuring greenhouse gas (GHG) emissions indicates human activities that lead to climate change. CO_2 is the primary GHG [1]. Consequently, New Zealand and many other countries have pledged to plummet their CO_2 emission. CO_2 emission is proportional to the electricity (Energy) consumption [2].

As another environmental issue, solid waste management is the biggest problem for authorities of cities of any size in developing countries worldwide. Some studies suggested that people who live in municipal solid waste (MSW) facilities nearby can experience low weight at birth, congenital anomalies, and some types of cancers. Mainly, MSW contains dangerous constituents such as heavy metals-containing waste, several chemicals, and many other substances. MSW can contribute to CO_2 emission when it is anaerobic, digested, and disposed of. Waste management imposes monetary challenges [3].

☆ Featured Application: Constant luminous flux driver for LEDs to optimise monetary burden for the owners.

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Despite decreasing trend of energy consumption share of the lighting in buildings' total energy consumption [4–6] -still the share is substantial-absolute figure of energy consumption of lighting systems continues to increase [6]. By mitigating the lighting systems' electrical power consumption, the contribution to the CO_2 emission of lighting systems can be reduced.

Incorporating LEDs in lighting systems aligns with the European countries' adherence to the nearly zero-energy concept outlined in the energy performance of buildings directive (EPBD). This approach has also been adopted by various other nations [7]. LEDs adhere to recommended standard ranges for photometric and colorimetric parameters within indoor environments [8]. Moreover, in studies examining outdoor LED lighting applications, pedestrians reported increased comfort. At the same time, drivers noted superior illumination uniformity on the street with LEDs compared to existing fluorescent streetlights at the exact location during night-time [9]. Thanks to their exceptional brightness, compact design, and efficiency, modern LED sources can achieve over 200 lm/W [5]. LEDs' long lifetime [10] is another advantage, leading to less waste than other light sources. Within almost ten years, the LED market share in lighting has surged to 70 %, to reach 100 % by 2025 [11,12].

Despite LED luminaire's high efficacy, their lifecycle environmental impacts pertinent studies [13–15] revealed that the usage, raw material extraction, and supply (including production and transport), and manufacturing stages contribute substantially to CO_2 emissions among all lifecycle stages. Among the most contributor stages, usage stage CO_2 emission is dominant.

According to the abovementioned, LEDs are now the dominant light source, leading to a lower carbon footprint due to their high efficacy compared to older light source technologies. Consequently, finding methods to manage and minimise their lifecycle financial burden for the owners is appealing. By finding the optimised interval for renewing LED luminaires simultaneously, energy usage leading to CO_2 emission and end-of-life waste will be managed, although the main goal is reducing the financial burden of the owners since the method of this paper is a trade-off of consumed energy and the light sources renewal costs.

1.2. *Constant lunimous flux outputs*

This research proposes a practical and applicable method for maintaining the initial luminous flux in LEDs to manage energy consumption in lighting systems to the required value. Furthermore, since the technique balances the cost and benefit of both energy usage and renewing LED luminaires, it simultaneously controls the waste amount since LED luminaires can be used until energy's over-usage cost surpasses the renewing cost.

To the authors ' best knowledge, the field of maintaining LED luminous flux constant does not consist of many scientific papers. There is a limited number of related documents. For example, Nishikawa et al. [16] proposed a method for LED luminance control by maintaining a constant current. The mentioned research works for only a limited duration and is not effective when aging degrades the LED efficacy. Jeong et al. [17] proposed a pn-junction temperature control method for controlling the optical properties of LED. The method is effective while the LED condition is not changed and, from this aspect, is similar to the previously mentioned research. Hegedüs et al. [18] proposed a CLO, originally designed to compensate for the temperature effect on LEDs' efficacy/efficiency depreciation based on the lookup tables obtained from LED tests. The CLO also can be used for aged LEDs. However, the LED isothermal characteristics records must be kept regularly during the LM 80-08 test. Bertin et al. [19] suggested a linear CLO adjusts supplied power to 70 % of LED nominal power and linearly increases the power. At the end of life, based on the L_{70} scheme, power reaches to 100 % for maintaining 70 % of the LED's nominal luminous flux during its lifetime. Notably, LED lumen maintenance during its lifetime is not linear [20]. Abbasinejad and Kacprzak [21] proposed a CLO compensating LED lumen depreciation during aging. They have not suggested a closed-form formula for calculating LED lumen deprecation at any time of the LED lifecycle.

1.3. *Paper structure*

In the rest of this paper, in section 2, the proposed method for maintaining fixed luminous flux and obtaining the best interval for LED renewing is explained in detail, and the mathematical foundation of the theory is proved. In Section 3, a case study will be conducted to assess the proposed research method. Finally, in section 4, the highlights of the research are outlined.

2. Proposed method

2.1. *Finding the supplied voltage by CLO for LED as a function of time*

It is essential to reduce delivered electrical power to the LED to the minimum required value for producing the initial desired luminous flux Φ_0. Hence, energy usage will be reduced to the minimum required value.

Luminous flux degradation during an LED's lifetime can be calculated by

$$\Phi_v(t) = \Phi_{v0} \bullet \exp(-\alpha t) \tag{1}$$

where $\Phi_v(t)$ is the luminous flux during LED's life cycle in *lumens*, Φ_{v0} is the initial luminous flux in *lumens*, and α is the decay rate constant, derived from Eq. (2).

$$\alpha = ce^{\left(\frac{-E_a}{K_B T_J}\right)} \tag{2}$$

where C is the pre-exponential factor, E_a is the activation energy in (eV), T_J is the pn-junction absolute temperature in$^\circ K$, and K_B is Boltzmann's constant ($8.617385 \times 10^{-5}\ eV/^\circ K$) [22,23].

The luminous and radiant flux relationship can be stated as Eq. (3).

$$\Phi_v = \Phi \bullet K_r \tag{3}$$

where Φ is radiant flux in *Watts*, and the international committee for weights and measures (CPIM), meeting at the international bureau of weights and measures near Paris, France, in 1977, defined (Kr) as the spectral luminous efficacy [24].

Then, radiant flux is proportional to luminous flux, and by keeping radiant flux fixed, the luminous flux can be kept constant or vice versa.

By separating LED current into two components, one radiating, which shapes LED's luminance, and the other non-radiating, and neglecting series resistance, LED current would be [25] as Eq. (4).

$$I_{Fpn} = I_{dis} + I_{rad} \tag{4}$$

where I_{Fpn} is the forward current of LED in *Amperes*, I_{dis} is the non-radiative current of LED in *Amperes*, and I_{rad} is the current related to the radiation in LED in *Amperes*.

The radiant flux of LED is

$$\Phi = I_{rad} \bullet V_{Fpn} \tag{5}$$

where V_{Fpn} is the forward voltage of an LED's junction.

By measuring the radiant flux (luminous flux) and LED forward voltage, I_{rad} can be obtained from Eq. (5). I_{rad} equals to

$$I_{rad}(V_{Fpn}) = I_{0rad} \bullet \left[exp\left(V_{Fpn} / (m_{rad} V_T)\right) - 1\right] \tag{6}$$

V_T=K_B.T_J is the thermal voltage; T_J denotes the absolute temperature of the pn-junction; m_{rad} is the ideality factor describing the I_{rad} component of an LED′s forward current. By multiplying both sides of Eq. (6) to V_{Fpn} Eq. (7) will be obtained.

$$I_{rad}(V_{Fpn}) \bullet V_{Fpn} = V_{Fpn} \bullet I_{0rad} \bullet \left[exp\left(V_{Fpn} / (m_{rad} V_T)\right) - 1\right] \tag{7}$$

then

$$\Phi(t) = V_{Fpn} \bullet I_{0rad}(t) \bullet \left[exp\left(V_{Fpn} / (m_{rad} V_T)\right) - 1\right] \tag{8}$$

Since, V_{Fpn} controls I_{rad}, then from Eq. (8), Φ is controlled by V_{Fpn}. Hence it is possible to compensate for radiant flux decay using forward voltage V_{Fpn}.

From Eq. (1), since radiant flux is consistently decaying, and Eq. (8) calculates the radiant flux, the next step is to recognise parts of the latter equation which are more responsible for radiant flux decay. A significant reason for LED aging is pn-junction temperature [23]. I_{0rad}, as radiant reverse saturation current, is also subject to change during the LED lifetime [23] and can effectively change the LED current from the Shockley model formula (Eq. (9)).

$$I = I_0 \bullet \left(exp\left(\frac{V_{Fpn}}{mK_B T_J}\right) - 1\right) \tag{9}$$

where I is the diode forward current in *Amperes*, I_0 is the diode reverse saturation current in *Amperes*, and m is the diode ideality factor, approximately 2 [26].

The goal is maintaining initial radiant flux during the LED lifetime.

By taking t=$0\ h$, while Φ_0 can be measured by equipment, for example, integrating sphere, the reverse saturation current I_{0rad} can be obtained from Eq. (10).

$$\Phi(0) = \Phi_0 = V_{Fpn} \bullet I_{0rad}(t) \bullet \left[exp\left(V_{Fpn} / (m_{rad} V_T)\right) - 1\right] \tag{10}$$

For commercial LEDs, often V_{Fpn} is 3–5V, m_{rad} is 1.1–2.4 [27], V_T is approximately 26 mV in 300$^\circ K$. Then Eq. (11) can be written.

$$exp\left(V_{Fpn} / (m_{rad} V_T)\right) \gg 1 \tag{11}$$

Therefore, I_{0rad} can be obtained from the initial luminous flux by Eq. (12).

$$\Phi(0) = V_{Fpn} \bullet I_{0rad} \bullet exp\left(V_{Fpn} / (m_{rad} V_T)\right) \tag{12}$$

$$\frac{V_{Fpn}}{(m_{rad} V_T)} = \ln\left(\frac{\Phi(0)}{V_{Fpn} \bullet I_{0rad}(t)}\right) \tag{13}$$

and, from Eq. (13) Eq. (14) will be obtained.

$$\frac{V_{Fpn}}{(m_{rad} V_T)} = \ln\left(\frac{\Phi_0}{V_{Fpn} \bullet I_{0rad}(t)}\right) \tag{14}$$

then Eq. (15) will be obtained.

$$\frac{V_{Fpn}}{(m_{rad}V_T)} = \ln\left(\frac{\Phi_0}{I_{0rad}(t)}\right) - \ln(V_{Fpn}) \tag{15}$$

which alternatively, can be stated as Eq. (16).

$$V_{Fpn} = (m_{rad}V_T)\left(\ln\left(\frac{\Phi_0}{I_{0rad}(t)}\right) - \ln(V_{Fpn})\right) \tag{16}$$

or as Eq. (17).

$$V_{Fpn} + (m_{rad}V_T)\ln(V_{Fpn}) = (m_{rad}V_T)\left(\ln\left(\frac{\Phi_0}{I_{0rad}(t)}\right)\right) \tag{17}$$

Since Eq. (18) holds true

$$V_{Fpn} \gg (m_{rad}V_T)\ln(V_{Fpn}) \tag{18}$$

then Eq. (19) can be achieved.

$$V_{Fpn} = (m_{rad}V_T)\left(\ln\left(\frac{\Phi_0}{I_{0rad}(t)}\right)\right) \tag{19}$$

and [23]

$$I_{0rad}(t) = I_{0rad}(0) + D \bullet \ln(t) = C + D \bullet \ln(t) \tag{20}$$

where D can be obtained by curve fitting, it should be noticed that Eq. (20) is accurate for $t > 100h$ [23].

Therefore

$$V_{Fpn} = (m_{rad}V_T)\left(\ln\left(\frac{\Phi_0}{C + D \bullet \ln(t)}\right)\right) \tag{21}$$

V_T as pn-junction thermal voltage can be calculated by measuring pn-junction temperature in an LED test duration of at least 6000 h [28]. Measuring is done using the transient testing method recommended in the JEDEC 51–5x family of standards. Pn-Junction temperature changes and shows linear properties after 340h of aging [23]. Then, only two points of pn-junction temperature measuring during LED type testing is enough, and it can be modelled as Eq. (22).

$$T_J = A \bullet t + B \tag{22}$$

Then, Eq. (21) can be rewritten as

$$V_{Fpn} = (m_{rad} \bullet K_B \bullet (A \bullet t + B))\left(\ln\left(\frac{\Phi_0}{C + D \bullet \ln(t)}\right)\right) \tag{23}$$

Therefore, a constant luminous flux can be obtained by applying a calculated voltage to the LED.

2.2. *Finding the right time to start voltage controlling*

Since LED mathematical models have some inaccuracies in the initial hours of LED lifetime introduced in previous research [23]-Eq. (23) obtained for constant luminous flux output for LED shows voltage decreasing in early hours of LED work. After a short duration, it shows an increase in the supplied forward pn-junction voltage, as expected. Since, in the very early hours of LED usage, according to being in its best quality and not yet affected by wear and tear mechanisms, it is rational to start voltage controlling by CLO driver after appearing strictly ascending property in Eq. (23) for V_{Fpn} in terms of time.

By derivation of Eq. (23) and setting it equal to zero, the global minimum and beginning time for using the voltage correction curve would be obtained (Eq.s (24)–(27)).

$$\frac{\partial V_{Fpn}}{\partial t} = (m_{rad} \bullet K_B \bullet (A \bullet t + B))'\left(\ln\left(\frac{\Phi_0}{C + D \bullet \ln(t)}\right)\right) + (m_{rad} \bullet K_B \bullet (A \bullet t + B))\left(\ln\left(\frac{\Phi_0}{C + D \bullet ln(t)}\right)\right)' = 0 \tag{24}$$

$$\frac{\partial V_{Fpn}}{\partial t} = m_{rad} \bullet K_B \bullet A \bullet \left(ln\left(\frac{\Phi_0}{C + D \bullet ln(t)}\right)\right) + (m_{rad} \bullet K_B \bullet (A \bullet t + B))\frac{-D}{t(C + D \bullet ln(t))} = 0 \tag{25}$$

$$\frac{\partial V_{Fpn}}{\partial t} = m_{rad} \bullet K_B \bullet \left[A \bullet \left(\ln\left(\frac{\Phi_0}{C + D \bullet ln(t)}\right)\right) - \frac{A \bullet D}{C + D \bullet \ln(t)} - \frac{B \bullet D}{t(C + D \bullet \ln(t))}\right] = 0 \tag{26}$$

$$A \bullet \left(\ln\left(\frac{\Phi_0}{C + D \bullet ln(t)}\right)\right) - \left(A + \frac{B}{t}\right) \cdot \left(\frac{D}{C + D \bullet \ln(t)}\right) = 0 \tag{27}$$

For an exact calculation of the CLO functioning starting time. And by following the conditions which are mentioned in Eq. (28),

$$A \ll \frac{B}{t} \ \& \ |\ln(\Phi_0)| \ll |\ln(C + D \bullet \ln(t))| \tag{28}$$

Eq. (27) can be reduced to

$$A \bullet (\ln(C + D \bullet \ln(t))) + \left(\frac{B}{t}\right) \cdot \left(\frac{D}{C + D \bullet ln(t)}\right) = 0 \tag{29}$$

Although the analytical solution for Eq. (29) is not easy, there are many numerical solution tools available now as a solution. Therefore, easily the starting time for CLO functioning is calculable.

2.3. Finding the right time to stop the voltage controlling (LED luminaire renewal time)

The roadmap for ending time for controlling the bias voltage of LED and renewing it would be calculating the ***time*** when the difference in cost of energy usage between an old luminaire and a new one outweighs the price of renewing the LED.

Since changing the linear term $(m_{rad} \bullet K_B \bullet (A \bullet t + B))$ is dominant in Eq. (23), V_{Fpn} changes approximately linearly, significantly when the LED age is extended. Also, from Ref. [23], changes in radiant and non-radiant parameters are similar.

From Eq. (23), for the long life of LED by knowing Eq. (30),

$$|\ln(\Phi_0)| \ll |\ln(C + D \bullet \ln(t))| \tag{30}$$

Eq. (31) can be written

$$V_{Fpn} = -(m \bullet K_B \bullet (A \bullet t + B))(\ln(C + D \bullet \ln(t))) \tag{31}$$

and, from Eq.s (9) and (31), Eq. (32) can be obtained.

$$I_{Fpn} = I_0 \bullet \left(exp\left(-\frac{(m \bullet K_B \bullet (A \bullet t + B))(\ln(C + D \bullet \ln(t)))}{m \bullet K_B \bullet (A \bullet t + B)}\right) - 1\right) = I_0 \bullet \left(\frac{1}{C + D \bullet \ln(t)} - 1\right) \tag{32}$$

By calculating I_0 from Eq. (33) [23].

$$I_0(t) = E + F \bullet \ln(t) \tag{33}$$

Since the changing regime of the LED current components is similar [23], Eq. (34) can be written.

$$I_{Fpn} = (E + F \bullet \ln(t)) \bullet \left(\frac{1}{C + D \bullet \ln(t)} - 1\right) \tag{34}$$

Since Eq. (35) holds true,

$$C + D \bullet \ln(t) \lll 1 \tag{35}$$

Then

$$I_{Fpn} \cong \frac{E + F \bullet \ln(t)}{C + D \bullet \ln(t)} \tag{36}$$

Then, from Eq.s (31) and (36), the LED power consumption would be

$$P_{LED}(t) = V_{Fpn} \bullet I_{Fpn} = -(m \bullet K_B \bullet (A \bullet t + B)) \bullet (\ln(C + D \bullet \ln(t))) \bullet \left(\frac{E + F \bullet \ln(t)}{C + D \bullet \ln(t)}\right) \tag{37}$$

According to the mentioned inaccuracies for the early time of LED operation, power formula (Eq. (37)) is valid after the CLO functioning start time is obtained, as calculated in section 2.2. Then, before the CLO operation starts, the LED power is fixed.

For moments before CLO operation starts, the LED consumed power would be

$$P_{LED}(t < t_{CLO\ Starting}) = V_{Fpn}(t_{CLO\ Starting}) \bullet I_{Fpn}(t_{CLO\ Starting}) \tag{38}$$

after the CLO operation starts,

$$P_{LED}(t > t_{CLO\ Starting}) = -(m \bullet K_B \bullet (A \bullet t + B)) \bullet (\ln(C + D \bullet \ln(t))) \bullet \left(\frac{E + F \bullet \ln(t)}{C + D \bullet \ln(t)}\right) \tag{39}$$

The total consumed energy would be

$$E_{LED} = \int_{t_{New\ LED\ START}}^{t_{End\ of\ using\ the\ new\ LED}} P_{LED}(t)dt \tag{40}$$

From Eq.s (38) and (39), P_{LED} is an ascending function. It is evident that after a duration, to maintain a constant luminous flux, a substantial value of energy compared to the initial moments of LED usage should be consumed. After a threshold, buying a new LED similar to the old one, consuming less power for the same luminous flux, is more beneficial than using the degraded old one.

LED luminaires consist of LED chips, and the majority of consumed energy in luminaires is used by LED chips; the luminaire consumed energy can be taken as the sum of the luminaire's LED chip's energy. Furthermore, a luminaire's total luminous flux is equal to the sum of individual LED chips [29]. Consequently, an LED chip's luminous flux degradation trend can be taken as the Luminaire's, and LED chip degradation and energy usage data are proportional to the corresponding data for luminaires.

The next step is to find the correct moment for renewing the old LED luminaires with the new one.

As illustrated in Fig. 1, the energy consumption of the old and new LED luminaire shows the better efficacy of the new one. However, given the considerable initial cost of buying a new LED luminaire, especially in bulk purchasing, changing LED luminaires in intervals shorter than a specific duration is not cost-effective.

Finding the right time to replace the LED luminaires gives the best clue for financial benefit while also managing CO_2 and end-of-life waste.

As illustrated in Fig. 1, when proposed CLO is used during an LED luminaire replacing interval, the instantaneous power consumption of a used LED luminaire is more significant than a new similar one. As shown in Fig. 1, the difference in energy consumption as the integration of the instantaneous power difference in terms of time is the red area (The blue area refers to the power of new LED luminaire).

By Eq.s (38)–(40), Eq.s (41) and (42) will be obtained.

$$\Delta E_{LED\ luminaire} = \int_{t_{New\ LED\ luminaire\ start}}^{t_{Next\ new\ LED\ luminaire\ start}} [p_{used\ luminaire\ LED}(t) - p_{new\ luminaire\ LED}(t)]dt \tag{41}$$

$$\begin{aligned}\Delta E_{LED\ luminaire} = &\int_{t_{New\ LED\ luminaire\ start}}^{t_{New\ LED\ luminaire\ CLO\ functioning\ start}} \Bigg[-(m \bullet K_B \bullet (A \bullet (t + t_{New\ LED\ luminaire\ start}) + B)) \bullet (\ln(C + D \bullet \ln(t + t_{New\ LED\ luminaire\ start}))) \\ &\bullet \left(\frac{E + F \bullet \ln(t + t_{New\ LED\ start})}{C + D \bullet \ln(t + t_{New\ LED\ start})}\right) - V_{Fpn_{fixed}} \bullet I_{Fpn_{fixed}} \Bigg] dt + \int_{t_{New\ LED\ luminaire\ CLO\ functioning\ start}}^{t_{Next\ new\ LED\ luminaire\ start}} -(m \bullet K_B \bullet (A \bullet (t + t_{New\ LED\ luminaire\ start}) + B)) \\ &\bullet (\ln(C + D \bullet \ln(t + t_{New\ LED\ luminaire\ start}))) \bullet \left(\frac{E + F \bullet \ln(t + t_{New\ LED\ luminaire\ start})}{C + D \bullet \ln(t + t_{New\ LED\ luminaire\ start})}\right) + (m \bullet K_B \bullet (A \bullet (t) + B)) \bullet (\ln(C + D \bullet \ln(t))) \\ &\bullet \left(\frac{E + F \bullet \ln(t)}{C + D \bullet \ln(t)}\right) dt\end{aligned} \tag{42}$$

where, $\Delta E_{LED\ luminaire}$ is the difference in energy usage between an old LED (luminaire) and a new one, $t_{new\ LED\ luminaire\ start}$ is the time of starting operation of the new LED (luminaire), $t_{Next\ new\ LED\ luminaire\ start}$ is the time of starting operation of the next new LED (luminaire), $t_{New\ LED\ luminaire\ CLO\ functioning\ start}$ is time that the CLO starts functioning for the new LED (luminaire), $p_{used\ luminaire\ LED}(t)$ is the instantaneous power of the old LED (luminaire), $p_{new\ luminaire\ LED}(t)$ is the instantaneous power of the new LED (luminaire), $V_{Fpn_{fixed}}$ is LED (luminaire) forward voltage before CLO functioning, and $I_{Fpn_{fixed}}$ is LED (luminaire) forward current before CLO functioning.

Since Eq. (43) holds true,

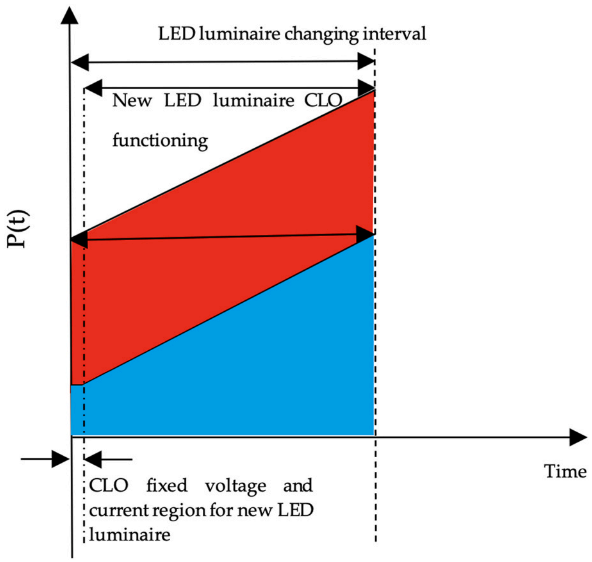

Fig. 1. Instantaneous power consumed by old and new LED luminaire in one LED luminaire replacing interval.

$$t_{New\ LED\ luminaire\ start} \ggg t_{LED\ luminaire\ CLO\ functioning\ start} \tag{43}$$

Therefore, the first integral term can be removed, and only it is possible to keep the second term. Then

$$\Delta E_{LED} \cong \int_{t_{New\ LED\ luminaire\ CLO\ functioning\ start} \cong 0}^{t_{Next\ new\ LED\ luminaire\ start} = t_{LED\ change}} -\left(m \bullet K_B \bullet \left(A \bullet \left(t + t_{LED\ luminaire\ change} + t_{New\ LED\ luminaire\ CLO\ functioning\ start}\right) + B\right)\right) \bullet \left(\ln\left(C + D \bullet \ln\left(t + t_{LED\ luminaire\ change} + t_{New\ LED\ luminaire\ CLO\ functioning\ start}\right)\right)\right) \bullet \left(\frac{E + F \bullet \ln\left(t + t_{New\ LED\ luminaire\ start} + t_{New\ LED\ luminaire\ CLO\ functioning\ start}\right)}{C + D \bullet \ln\left(t + t_{New\ LED\ luminaire\ start} + t_{New\ LED\ luminaire\ CLO\ functioning\ start}\right)}\right) + \left(m \bullet K_B \bullet \left(A \bullet (t) + B\right)\right) \bullet \left(\ln(C + D \bullet \ln(t))\right) \bullet \left(\frac{E + F \bullet \ln(t)}{C + D \bullet \ln(t)}\right) dt \tag{44}$$

The benefit of energy consumption would be as Eq. (45).

$$Cost\ of\ energy\ benefit = \Delta E_{LED}\left(t_{LED\ luminaire\ Change}\right) \bullet (Cost\ of\ energy\ unit) \tag{45}$$

The old and new LED luminaire energy consumption difference calculated in Eq. (44) is for an interval of replacing the LED luminaire. For obtaining the best interval for LED luminaire replacement, a duration T is defined, which includes n LED luminaire changing intervals (τ) (Fig. 2).

For duration T, the total cost, including the energy consumption difference between old and new LED luminaires for each interval and the cost of purchasing new LED luminaires at the beginning of each interval, can be obtained from Eq.s (46)–(48) consequently.

$$cost(T) = -n \bullet (Cost\ of\ energy\ unit) \bullet \Delta E_{LED\ luminaire} + nCost_{new\ LED\ luminaire} \tag{46}$$

$$cost(T) = -n \bullet (Cost\ of\ energy\ unit) \bullet \int_{t_{New\ LED\ luminaire\ CLO\ functioning\ start} \cong 0}^{t_{Next\ new\ LED\ luminaire\ start} = t_{LED\ change}} \left[p\left(t + t_{LED\ luminaire\ Change}\right) - p(t)\right] dt + nCost_{new\ LED\ luminaire} \tag{47}$$

$$t_{LED\ luminaire\ Change} = \tau \Rightarrow cost(T) = -\frac{T}{\tau} \bullet (Cost\ of\ energy\ unit) \bullet \int_0^{\tau} [p(t+\tau) - p(t)]dt + \frac{T}{\tau} Cost_{new\ LED\ luminaire} \tag{48}$$

The negative sign of the cost of energy unit in Eq. (46) shows that the energy consumption difference term is of profit, not loss (New LED luminaire consumes less energy than old one).

By setting the derivative of Eq. (48) in terms of LED luminaire replacing interval to zero (Eq. (49)), the minimum cost for the optimum benefit could be obtained.

$$\frac{\partial cost(T)}{\partial \tau} = -\frac{T}{\tau^2} \bullet \left[\left((-Cost\ of\ energy\ unit) \bullet \int_0^{\tau} [p(t+\tau) - p(t)]dt\right) + Cost_{new\ LED\ luminaire}\right] + \frac{T}{\tau} \bullet (-Cost\ of\ energy\ unit) \bullet \frac{\partial[P(2\tau) - P(\tau) - P(\tau) + P(0)]}{\partial \tau} = 0 \tag{49}$$

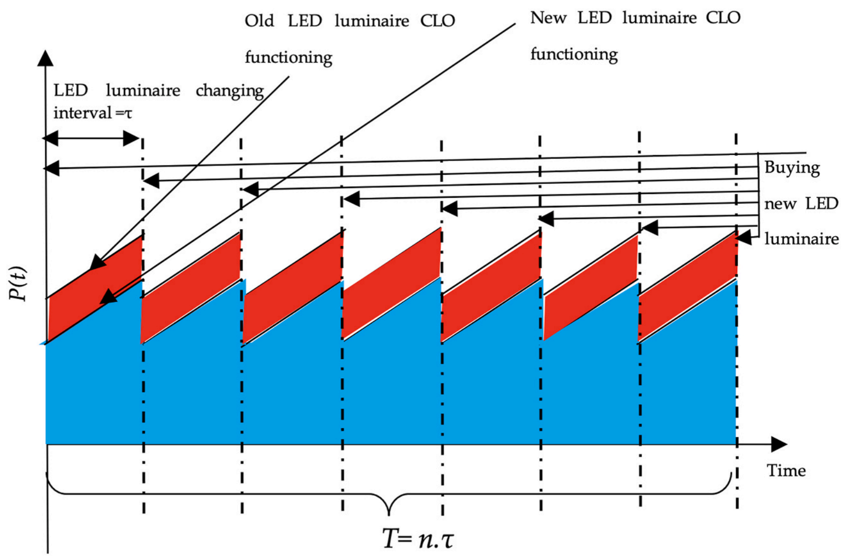

Fig. 2. Illustration of energy and buying new LED luminaire intervals in an arbitrary duration T.

which can be simplified as Eq. (50).

$$\frac{\partial cost(T)}{\partial \tau} = -\frac{1}{\tau} \bullet \left[\left((- Cost\ of\ energy\ unit) \bullet \int_0^{\tau} [p(t+\tau) - p(t)]dt \right) + Cost_{new\ LED\ luminaire} \right] + (- Cost\ of\ energy\ unit) \bullet [2p(2\tau) - 2p(\tau)] = 0 \tag{50}$$

Consequently

$$\int_0^{\tau} [p(t+\tau) - p(t)]dt + 2\tau[p(2\tau) - p(\tau)] = \frac{Cost_{new\ LED\ luminaire}}{Cost\ of\ energy\ unit} \tag{51}$$

By changing the LED luminaire renewing time ($t_{LED\ change}=\tau$), a match of ***energy saving benefit*** and ***new LED luminaire price*** from Eq. (51) can be obtained.

It worth mentioning all intrinsic parameters are needed for proposed method can be obtained by accessible instruments and devices, during the LM 80-08 test, although they are not directly included in LM 80-08 [28].

By finding this close-to-exact formula for adjusting the voltage for LEDs, there is no error for supplied electrical power. While the correct illuminance is maintained, only necessary electrical energy is consumed. Therefore, energy usage would be the optimum, and the CO_2 emission and, based on finding the optimum LED luminaire renewal interval, end-of-life waste are also at their minimum required value.

3. Case study

In this section, an LED model obtained [23] is examined and discussed to show applicability of the proposed formula for obtaining necessary forward voltage as a function of time for maintaining constant initial luminous flux during the LED lifetime. Furthermore, the validation of the method of finding the optimum interval of LED luminaires renewal in terms of financial burdens is assessed.

For finding the best fit (factors A, B, C, and D in Eq. (31)), first in some measuring times (it is better to correspond to measuring times in LM 80-08) luminous flux, pn-junction temperature, and forward voltage (Φ_v, T_J, and V_{Fpn}) should be measured. The procedure for measuring these parameters is well-known. These parameters lead to finding I_{0rad} from Eq. (20) in measuring times. By using found (I_{0rad})s in measuring times and using Eq. (20) for curve fitting, a consistent formula for $I_{0rad}(t)$ could be found.

For LED sources whose data exists [23] and are used in this case study, the $I_{0rad}(t)$ function, by fitting the log-normal function as stated in the mentioned paper, can be obtained as illustrated in Fig. 3.

$$I_{0rad}(t) = -1.10741 \times 10^{-18} + 1.82232 \times 10^{-19} \ln(t) \tag{52}$$

Also, based on measurements for LED during the test (Fig. 4), $T_J(t)$ at standard ambient temperature (298° K) would be [23].

$$T_J(t)^{^\circ K} = 373 + \left(\frac{t}{225}\right) \tag{53}$$

The initial radiant flux is 400 mW [23]. The ideality factor can be considered as its average value in commercial LEDs (approximately 1.8), or if it is given as the LED source studied in Ref. [23], an approximation from the given curve can be used (approximately 2.2).

Therefore, by having Eq.s (23), (52) and (53) the formula of V_{Fpn} which can be directly applied to the LED source during its lifetime to obtain fixed luminous flux, would be

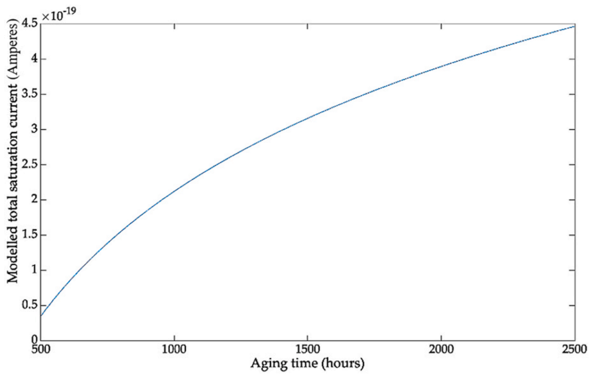

Fig. 3. Modelled optical saturation current curve fitting as a function of time.

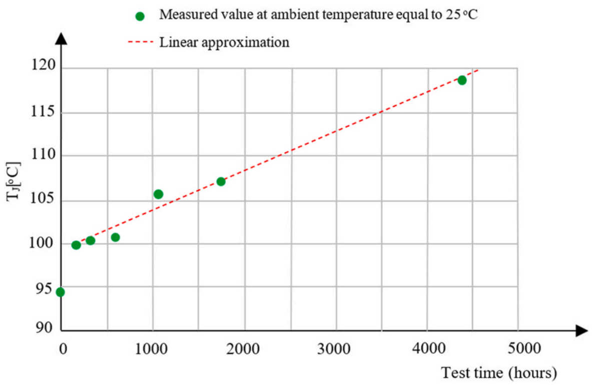

Fig. 4. Modelled pn-junction temperature curve fitting as a function of time.

$$V_{Fpn} = \left(2.2 \bullet 8.617385 \times 10^{-5} \bullet \left(373 + \left(\frac{t}{225}\right)\right)\right)\left(\ln\left(\frac{0.41}{-1.10741 \times 10^{-18} + 1.82232 \times 10^{-19}\ln(t)}\right)\right) \tag{54}$$

Eq. (54) is the forward voltage applied to the LED source during its lifetime to maintain a fixed radiant and luminous flux. The implementation can use a microprocessor controller, in which factors A, B, C, and D are given to its memory, say EPROM, to calculate the supplied voltage for the CLO driver at each moment.

Using Eq. (29), the starting time for CLO will be calculated at this stage.

$$\frac{\partial V_{Fpn}}{\partial t} = 0.00018 \bullet \left(0.0444\,\text{In}\left(\frac{0.41}{-1..10741 \bullet 10^{-18} + 1.8.223210^{-19} \bullet \ln(t)}\right)\right)_{-}\left(\frac{8.0992 \times 10^{-22}(83925 + t)}{t\left(1.82232\bullet 10^{-19}\ln(t) - 1.10741\bullet 10^{-18}\right)}\right) = 0 \tag{55}$$

The starting time can be obtained by plotting the curve, as shown in Fig. 5.

As can be understood from Fig. 5, the starting point from proposed method from Eq. (55) would be 1581h from beginning of the LED operation.

The next step is finding the LED source usage interval ending time for replacing the old LED source with a new one.

First, the reverse saturation current of the LED source should be obtained as a function of time. By fitting a curve as Eq. (33), $I_0(t)$ would be obtained (Fig. 6) from Eq. (56).

$$I_0(t) = -1.55351 \times 10^{-18} + 2.55607 \times 10^{-19}\ln(t) \tag{56}$$

From Eq. (51), the best compromise between energy consumption difference cost between old and new LED sources on one hand and the cost of buying a new LED source on the other hand would be

$$\int_0^{\tau}[p(t+\tau) - p(t)]dt + 2\tau[p(2\tau) - p(\tau)] = \frac{Cost_{new\ LED}}{Cost\ of\ energy\ unit} \tag{57}$$

where, τ is LED luminaire changing interval as stated in Eq. (58).

$$\tau = t_{LED\ change}, \tag{58}$$

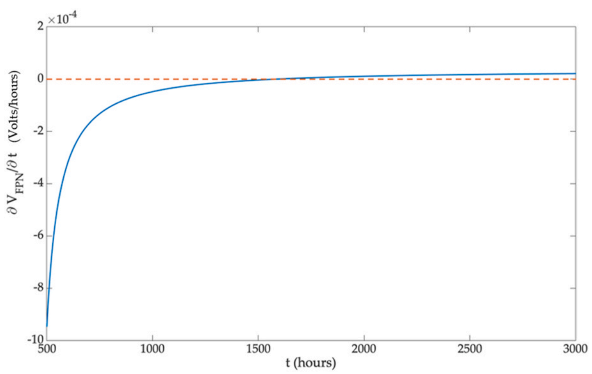

Fig. 5. Derivative of LED pn-junction forward voltage as a function of time.

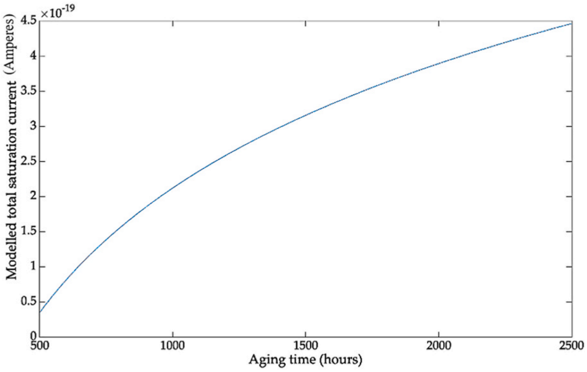

Fig. 6. Modelled total saturation current by curve-fitting as a function of time.

By inserting numbers into Eq. (39), instantaneous power can be calculated as is shown in Eq. (59).

$$p(t) = -\left(2.2 \bullet 8.617385 \times 10^{-5}_{\bullet}\left(\frac{t}{225}+373\right)\right)_{\bullet}\left(\ln\left(-1.10741 \times 10^{-18} + 1.82232 \times 10^{-19} \bullet \ln(t)\right)\right)_{\bullet} \left(\frac{-1.55351 \times 10^{-18} + 2.55607 \times 10^{-19} \bullet \ln(t)}{-1.10741 \times 10^{-18} + 1.82232 \times 10^{-19} \bullet \ln(t)}\right), \tag{59}$$

and,

$$\frac{Cost_{new\ LED}}{Cost\ of\ energy\ unit} = \frac{14.00\ \$}{0.001722\ \$} = 81300.813 \tag{60}$$

Now, Eq. (60) value should be applied to Eq. (57). By changing the $\tau = t_{LED\ change}$ in a reasonable domain, the right time for LED source renewal will be easily obtained. In Table 1 checkpoints that end up with the right solution are illustrated based on energy price of 0.001722 $ per watt hour and the price for a type of LED lighting source equal to 14 $. A graphical illustration of checkpoints compared to the LED source price can be seen in Fig. 7.

The proposed method obtained the right time for LED source renewal, 23,832 *h* after its operation started.

The obtained interval is the exact time that minimises unnecessary energy consumption while simultaneously minimising LED source replacement times.

Finding an approach for supplying the needed power for lighting systems avoids unnecessary energy consumption and renewing LED source. Hence, it results in minimal required CO_2 emissions and waste, reducing the owner's financial burden.

4. Conclusions

In recent decades according to detrimental effects of climate changing on the global environment and as a result too much regards on the CO_2 emissions many countries have internationally pledged to reduce CO_2 emissions to the environment. Hence, the widespread adoption of LED lighting instead of traditional light sources, have become common globally.

Since LEDs have long lifetimes, they are unlikely to experience catastrophic failure. Therefore, as other semiconductor-based devices, they are subjected to gradually degradation in the form of luminous flux depreciation and as a result CLOs are used to compensate the degradation. CLOs inject increasing instantaneous energy to LEDs to take their output to the desired value. Although, new LED luminaires result in less energy usage, procurement of new luminaires has a financial burden for the owners.

In this paper a formula was proposed for maintaining the initial luminous flux in LEDs using CLOs for providing the users with visual comfort, based on mathematical model of LEDs. This formula makes it possible to maintain the initial luminous flux of an LED throughout its lifetime with minimal energy consumption. Moreover, since CLOs' over energy injection requires paying more for electricity. An exact method was proposed to optimise the LED luminaire renewing interval by calculating the trade-off of CLOs' over-energy consumption for the old luminaire and new luminaire cost.

For such exact CLO systems, knowing LED mathematical model parameters is vital. Therefore, this paper suggests adding pn-junction temperature, and ideality factor measuring to LM 80-08 standard method for using in CLOs design.

Developing a strategy to provide precisely the required energy for lighting systems and timely LED replacement prevents unnecessary energy usage and LED renewal. Consequently, besides minimising financial burdens for the owners, it helps manage CO_2 emissions and waste.

Data availability

"Data included in article referenced in the article."

Table 1
Moments are checked for finding the best interval for LED sources replacement.

$t_{LED\ change}$ hours	Cost of new LED source/Cost of energy unit
1,500	75.72
2,000	276.34
4,000	1836,23
8,000	8537.79
16,000	36,104.23
20,000	56,935.48
23,832	**81,300.81**
32,000	147,538.17
40,000	231,326.89

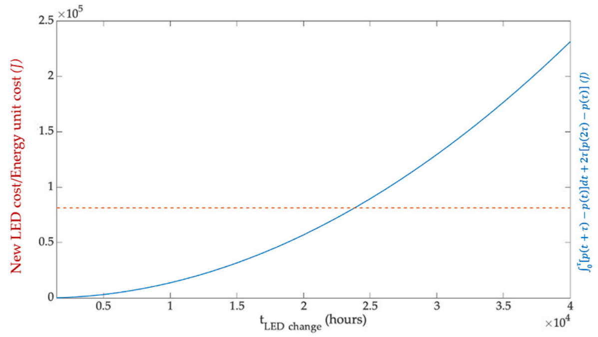

Fig. 7. Graphical illustration of optimum replacing LED source interval.

CRediT authorship contribution statement

Reza Abbasinejad: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dariusz Kacprzak:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, **Dulsha Kularatna-Abeywardana:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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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