ENERGY SAVINGS AND MAINTENANCE OPTIMIZATION OF ENERGY-EFFICIENT LIGHTING RETROFIT PROJECTS INCORPORATING LUMEN DEGRADATION

by

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SUMMARY

ENERGY SAVINGS AND MAINTENANCE OPTIMIZATION OF ENERGY-EFFICIENT LIGHTING RETROFIT PROJECTS INCORPORATING LUMEN DEGRADATION

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Keywords:	Energy-efficient lights, luminous flux degradation, lighting system performance degradation, lumen degradation failure modeling, lighting retrofit optimization problem, economic analysis.

The lighting retrofit method is adopted as one of the solutions to reduce lighting energy consumption and improve lighting quality in existing buildings. Lighting controls and energy-efficient light sources are used to achieve the goals of the lighting retrofit. Nowadays, Light-Emitting Diodes (LEDs) are replacing traditional lighting technology owing to their high efficiency and longevity. One of the advantages of LEDs is the controllability function, which allows users to set the light level according to their preferences. This saves more energy and satisfies users' lighting needs. However, over time, the performance of lighting retrofit projects deteriorates subject to failure of the retrofitted lights. Therefore, to maintain the performance of lighting retrofit projects, maintenance must be planned and performed.

The impacts of the users' lighting level requirements on LEDs' life characteristics and lighting system performance are investigated by using lighting controls. 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. 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, 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. Light levels at workspace are modelled using the lumen method. This model helps to quantify energy savings and predict when lamps will fail to deliver the required light levels. In existing studies, users' lighting level requirements are neglected when investigating the lifetime of the lighting system; however, users' profile and driving schemes affect the operating conditions of a lighting system. From the simulation results, it is noted that lumen output degradation increases when the user's set illuminance is above the illuminance required under normal operating conditions and decreases when the user's set illuminance is below the illuminance required under normal operating conditions. Increased lumen output degradation shortens the lifetime of LEDs and reduces energy savings, while decreased lumen output degradation extends the lifetime and increases energy savings.

Generally, lighting retrofit projects contain a large lighting population; investigating when each lamp will fail can be time-consuming and costly. In this research, a mathematical model is formulated to model LEDs' failure by analysing the statistical properties of the lumen degradation rates. Based on the statistical properties of the degradation rates, the cumulative probability of failure distribution and the survival function are modelled. The formulated survival function is incorporated into the lighting maintenance optimization problem to balance energy savings and maintenance costs. A case study carried out shows that, in 10 years, the optimal lighting maintenance plan would save up to 59% of lighting energy consumption with acceptable maintenance costs. It is found that the proposed maintenance plan is more cost-effective than full maintenance. It is concluded that lumen degradation failure should be considered when investigating the performance of lighting retrofit projects, as this may not only affect energy savings but also reduce the level of illumination, which can cause visual discomfort.

The initial investment costs of LEDs are still a barrier to the implementation of LED lighting systems in residential buildings. Energy-efficiency projects often face hurdles to access capital investments because decision-makers and funders do not have enough information about operational savings the project can provide and specific financial requirements applied to efficiency investment. In this research, an optimization model is formulated to give decision-makers and funders detailed information about the performance and operational savings that a LED lighting retrofit project can offer and its economic viability. The lumen degradation failure model developed is used to monitor and estimate the energy savings, and the optimal maintenance plan is scheduled to replace failed lamps. In the existing studies, the economic analysis of the lighting retrofit projects is assessed based on lighting population decay due to burnout failure while in this research economic analysis is assessed by considering the lumen degradation failure. The case study results show that the substitution of halogen light bulbs with LED light bulbs could save up to 291.4 GWh of energy consumption, and reduce 273.92×10^3 tons of CO_2 emissions over 10-year period. The optimization model formulated is effective to help the decision-makers and funders to quantify the savings and assess the economic viability of the LED lighting retroïňĄt project. This optimization model can help the decision-makers and funders to make an informed decision.

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LIST OF ABBREVIATIONS

AC	Alternative current
CDM	Clean development mechanism
CFLs	Compact fluorescent lamps
CIBSE	Chartered Institution of Building Services Engineers
CICS	Constant illuminance control strategy
CM	Corrective maintenance
CRI	Colour-rendering index
CT	Colour temperature
DHCS	Daylight harvesting control strategy
EE	Energy-efficient
FEMP	Federal energy management program
GHG	Greenhouse gas
HID	High-pressure gas discharge
HPL	High-performance lamps
IEA	International energy agency
IES	Illuminating Engineering Society
IPMVP	International performance measurement and verification protocol
IR	Infrared radiation
LED	Light-Emitting Diode
LLF	Light loss factor
MH	Metal-halide
MIDACO	Mixed Integer Distributed Ant Colony Optimization
MTBF	Mean time between failures
M&V	Measurement and verification
PELP	Polish Efficient Lighting Project
PM	Preventive maintenance
SCIP	Solving constraint integer program
UGR	Unified glare rating
UF	Utilization factor
UP	University of Pretoria

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CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

Global warming is a key aspect of climate change. Currently, climate change is the greatest threat the world is facing. The main cause of global warming is the burning of fossil fuels such as coal and oil, which produces greenhouse gases (GHGs). In many countries, electricity used in buildings is mainly produced by coal-fired power stations. According to the South African energy sector report [1], 59% of the electricity used in South Africa comes from coal. Over the last decade, energy consumption in buildings has increased considerably, which increased GHG emissions. In South Africa, energy consumption in the residential sector increased from 16% in 1993 to 27% in 2015 [1]. One of the solutions to reduce GHGs released during the combustion of fossil fuels is to reduce electricity consumption in buildings. Heating, ventilation, air-conditioning, and lighting consume the highest portion of the electricity used in commercial and residential buildings [2, 3]. Therefore, these areas offer significant opportunities for improvement in building energy efficiency.

One of the solutions for lighting energy efficiency improvement is retrofitting. Retrofitting refers to the modification and refurbishment of the existing system to improve energy efficiency. From the lighting point of view, retrofit is referred to as an upgrade of light fixtures or lamps to increase lighting quality with less energy consumption. To achieve these goals, two main approaches are used: (1) supply the required light using less energy, and (2) supply light only when and where it is needed. The first approach is achieved by using energy-efficient (EE) light sources [4], and the second approach is achieved by using lighting controls such as motion sensors, occupancy sensors, and dimmers [5]. EE light sources are characterized by high luminous efficacy and a long lifetime. Currently, LEDs are the most EE lighting technology with luminous efficacy between 20 - 150 lm/W, and a lifetime ranging between 15 000 - 100 000 hours [6].

The performance of retrofit projects may degrade owing to the failure of the retrofitted items [7]. For the EE lighting retrofit project, the performance is generally deteriorated by two main failures: burnout/catastrophic failure and degradation failure. Degradation failure, also called wear-out failure, is caused by increased wearing and ageing of the material. The most common degradations in electric lights are lumen degradation and colour shift [8]. The causes of lumen degradation differ from one lighting technology to another. The main cause of lumen degradation in LEDs is the heat generated at the LED junction [9]. If LEDs are not supplied with an appropriate heat-sink to dissipate the generated heat (during operation) away from the system, the junction temperature will rise. Higher junction temperature can increase the degradation rate of the LED. Because of the longevity of LEDs, burnout failure is negligible and lumen degradation is used as the key factor in defining the lifetime of LEDs [10, 11]. To maintain the performance of retrofit projects, maintenance is necessary.

Maintenance is defined as all work (e.g., cleaning, repairs, replacement, etc.) undertaken or required to maintain an item or system in good and workable production conditions. Based on when (before or after failure) the maintenance is performed, maintenance can be classified into two main categories [12]; corrective maintenance (CM), and preventive maintenance (PM). CM is performed after a failure has occurred, while PM is performed before a failure has occurred. Unlike CM, PM is performed according to a schedule. Based on the aforementioned lamp failure modes, in a lighting system CM is carried out once the lamp has burnt out, and PM can be scheduled either based on usage of the lamp (e.g., every 1 000 h, 10 000 h, etc.), time-based (e.g., every week, every month, every year, etc.), or condition-based (e.g., lumen degradation and illumination level). PM enhances the efficiency of equipment, keeping them running more efficiently. However, the implementation of the PM can be time-consuming and costly because of the tasks performed, such as continuous monitoring of the working condition of the item. Therefore, the effective PM should be prioritized to balance maintenance costs and benefits. In order to balance maintenance costs and benefits, an optimization approach should be applied.

From a maintenance perspective, optimization is about finding an optimum solution that meets the objective-specific conditions. Optimization covers four main processes, including modelling the system function, identifying the design variables, setting an objective, and obtaining a solution from the model. The first step in designing a maintenance optimization problem is to determine the objective of the problem to be solved. The design variables are the parameters to be determined to achieve the best solution under given constraints. Depending on the available information about the states of factors influencing the system, the maintenance optimization models are classified into three categories [13];

certainty, risk, and uncertainty. The certainty model uses graphs to present optimal solutions [14]. In the risk model, the states of the influencing factors are known. Based on current information on the states of the influencing factors, future possible conditions can be predicted to determine the suitable optimal plan [15]. For the uncertainty model, future conditions and their corresponding probabilities are not known [16].

1.2 RESEARCH MOTIVATION

LEDs have gained attention in lighting retrofit projects during the past few years mostly because of their longevity and high efficiency. One of the main advantages of LEDs is the controllability function. The brightness of LEDs can be dimmed up to 10% of light output. This allows users to set the light level at their preferences. Enabling users to control the light level at their workspaces not only saves more energy, but also improves user's visual comfort by reducing eye strain and fatigue, and improving concentration. However, the lumen output of LED lights degrades over time and may be inadequate to provide the required illumination level to carry out a task safely, which may lead to visual discomfort. Literature studies [17, 18, 19] have shown that lumen output degradation and the lifetime of LEDs are highly affected by the junction temperature, and the junction temperature depends largely on the driving current. High junction temperature accelerates lumen degradation and reduces life characteristics. Since dimming the brightness of lights results in low driving current and junction temperature, dimming may increase the life characteristics of LEDs. In existing studies, lumen degradation and the lifetime of LEDs were analysed under several specific conditions, including constant driving current and junction temperature. However, driving current and junction temperature may vary depending on the user profiles and driving schemes. For this reason, further investigation is necessary to identify the impact of users' lighting level requirements on both LEDs' life characteristics and lighting system performance overall.

In lighting retrofit projects, retrofitted lights fail over time mainly owing to burnout and lumen degradation failures. These failures result in a reduced illumination level and lower project savings if proper maintenance is not performed. It is, therefore, necessary to plan and execute effective maintenance to maintain the performance of lighting retrofit projects. Previous studies investigated the lighting maintenance plan by modelling the lamp population decay due to burnout failure. It is noticed that lumen degradation failure is not considered in the existing lighting maintenance plans. Lumen degradation should not be overlooked, because it results in a reduced illumination level, which can cause visual discomfort.

Although LEDs would save significant lighting energy consumption and reduce carbon dioxide emissions, the implementation of LEDs in residential and commercial buildings is still at a low level, especially in developing countries. The question then is, why has this technology not been taken advantage of? Literature studies have shown that the implementation of energy-efficiency projects often faces hurdles to access capital investments because decision-makers and funders do not have enough information about the actual energy and cost savings from the project. Therefore, studies that can help decision-makers and funders to quantify and monitor the performance and analyse economic viability are necessary to promote the implementation of LED lighting retrofit projects.

1.3 RESEARCH OBJECTIVES AND SCOPE

The main objectives of this research are:

i. to investigate the impact of users' lighting level requirements on LEDs' life characteristics and lighting system performance;
ii. to model the LED lamp failure based on lumen degradation;
iii. to design an optimal lighting maintenance plan that takes into account the lumen degradation failure;
iv. to formulate an optimization model that can help decision-makers and funders to obtain detailed information about the performance and operational savings that an EE lighting retrofit project can provide.

The lumen degradation model is formulated to estimate energy savings accurately and enhance the lighting quality of EE lighting retrofit projects. An optimal maintenance plan is formulated to optimize the performance and maintenance costs of EE lighting retrofit projects. An optimization model is formulated to help decision-makers and funders quantify the savings and assess the economic viability of the EE lighting retrofit project. This will help decision-makers and funders to make an informed decision about the implementation of EE lighting retrofit projects.

The research hypotheses are; (1) when lumen degradation is monitored, lamps can be replaced before the lumen output reaches the human eye's lumen degradation threshold. This can improve the productivity and concentration of users by minimizing eye strain and level of fatigue problems due to an inadequate illumination level, and maintain the energy savings, (2) the lighting system performance is enhanced when maintenance is carried out, and building owners/managers benefit economically when maintenance is scheduled, (3) when decision-makers and funders have enough information about the energy efficiency performance and operational savings of energy efficiency projects, they can encourage and promote the implementation of these.

This research focuses on users' illumination level requirements, lumen degradation failure, lighting maintenance optimization problem, and economic analysis of an EE lighting retrofit project to understand the following matters better:

- impact of variation of driving current and operating junction temperature on the LED-based lighting system performance and lifetime;
- impact of lumen degradation on the performance of EE lighting retrofit projects;
- ways in which a lighting maintenance plan can be formulated into an optimization problem;
- the economic viability of EE lighting retrofit projects.

In this research, an academic office and residential buildings are studied. In the academic office, an LED lighting system is retrofitted with a lighting control system to save more energy and maintain the user's illumination requirement at a constant level. For residential buildings, LED light bulbs replace halogen bulbs to reduce lighting energy consumption and improve lighting quality. Residential and office buildings are chosen as the case studies in this research because they are among the highest consumers of lighting energy.

1.4 RESEARCH OUTPUTS

1.4.1 Journal papers

A. Ikuzwe, X. Xia, and X. Ye. Optimization model for energy savings and economic analysis of LED lighting retrofit projects. *Under Review.*

A. Ikuzwe, X. Xia, and X. Ye. Maintenance optimization incorporating lumen degradation failure for energy-efficient lighting retrofit projects. *Applied Energy 267 (2020): 115003.*

A. Ikuzwe, X. Ye, and X. Xia. Energy-maintenance optimization for retrofitted lighting system incorporating luminous flux degradation to enhance visual comfort. *Applied Energy 261 (2020):114379.*

1.4.2 Conference papers

A. Ikuzwe, X. Xia, X. Ye. Optimal maintenance plan with lumen degradation failure for energy-efficient lighting retrofit projects. 11^{th} *International Conference on Applied Energy (ICAE), Aug. 12-15, 2019, Västerås, Sweden.*

1.5 RESEARCH CONTRIBUTION

The contributions of this research are as follows:

- The formulation of the luminous flux degradation model, which takes into account users' lighting level requirements. This model helps to estimate the luminous flux degradation following the users' set light levels.
- The formulation of LEDs lumen degradation failure model based on statistical properties of lumen degradation rates.
- The formulation of the energy-maintenance optimal model, which takes into account luminous flux degradation. This model maximizes energy savings and minimizes maintenance costs. With this model, it is possible to predict when maintenance should be performed, how many times and how many lamps need to be replaced during maintenance. By considering luminous flux degradation, the formulated maintenance plan maintains the illumination level adequate to carry out tasks safely, which avoids visual discomfort.
- An optimization model for EE lighting retrofit projects, which takes lighting system performance degradation, savings, and economic issues into account, is developed to promote the implementation of LED lighting retrofit projects. This model gives decision-makers and funders detailed information about the energy efficiency performance and operational savings that a

LED lighting project can provide, and the specific financial requirements applied to investments in efficiency. In the existing studies, the performance degradation of the EE lighting system and the optimization problem are not considered to help decision-makers and funders make an informed decision.

1.6 THESIS OVERVIEW

This thesis is organized as follows:

Chapter 2 provides the background and literature review on artificial light sources and lighting systems. Existing artificial light sources are reviewed, and their failure modes and modelling are discussed. EE lighting system design, retrofit, and maintenance are reviewed and discussed.

Chapter 3 studies an energy-maintenance optimization model that considers luminous flux degradation. In this chapter, the lumen degradation of LED lights is modelled based on the variation in the operating junction temperature due to the users' lighting level requirements, and the optimization model is formulated to maximize energy savings and minimize maintenance costs while maintaining users' lighting requirements.

Chapter 4 presents an optimal lighting maintenance plan based on lumen degradation failure. The lumen degradation failure is modelled based on the statistical properties of degradation rates. By using the Kaplan-Meier method, the formulated lumen degradation failure is used to model the surviving population. The surviving population model is used to design an optimal lighting maintenance plan, which maximizes energy savings and minimizes maintenance costs.

Chapter 5 presents an optimization problem that can help decision-makers and funders to make an informed decision about the implementation of EE lighting retrofit projects. Energy savings are monitored and quantified. Lighting population degradation is modelled and optimal maintenance is scheduled to maintain project performance. Net-present value and payback period are used to analyse the project's economic viability.

Chapter 6 provides the summary and conclusion of the work done and offers suggestions for future work.

CHAPTER 2 LITERATURE REVIEW

2.1 CHAPTER OVERVIEW

This chapter covers the background and literature review of lighting systems. Topics covered in this chapter include the existing lighting technologies, lighting system design, lighting retrofitting, electric lights failure modes and modelling, and lighting maintenance. These are detailed in Figure 2.1.

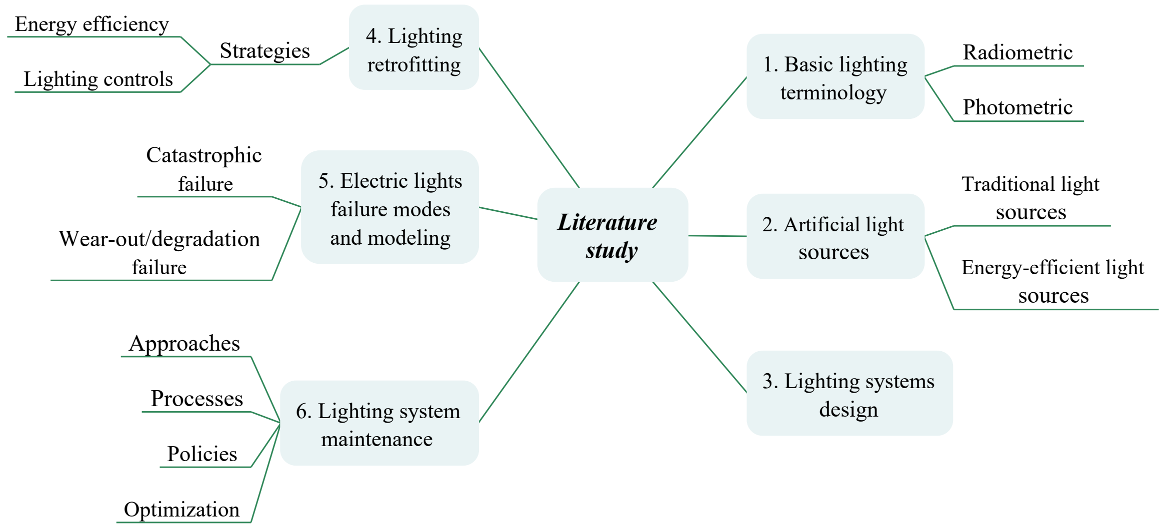

Figure 2.1. Topics covered in the literature study.

2.2 BASIC LIGHTING TERMINOLOGY

Lighting is referred to as the use of electric lights and daylight to achieve a practical effect. This research focuses on lighting using artificial light sources (electric light sources). Lighting using artificial light sources can be classified based on how electric light fixtures distribute light. This classification includes [20]:

i.) *Task lighting*

Task lighting is lighting that illuminates a particular area in a given space and facilitates the execution of a task.

ii.) *Accent lighting*

Accent lighting also referred to as highlighting, focuses light on a certain zone or object. It is usually used to showcase works of art or other attention-demanding activities such as concert-stage lighting.

iii.) *General lighting*

General lighting illuminates a general area to provide uniform illuminance over the space.

For general lighting applications, lighting is assessed using two main criteria, quantity and quality. These are further discussed in the next subsections.

2.2.1 Lighting quantity

Lighting quantity is a measure of light available at a surface or in a room. The following measures are used to measure the lighting quantity [21]:

i. *Luminous flux (ϕ)* is the quantity of light emitted by a light source. It is measured in lumen (lm).

ii. *Illuminance (E)* is the quantity of luminous flux falling on a surface. It is measured in lux (lx). Illuminance is mathematically expressed as

$$E = \frac{\phi}{Area\ (m^2)}. \tag{2.1}$$

iii. *Luminance (L)* measures the luminous intensity per unit area of light travelling in a given direction. The unit of luminance is candela per square meter (cd/m^2). Luminance is mathematically expressed as

$$L = \frac{I}{A_L \cos\varepsilon}, \tag{2.2}$$

where $A_L \cos\varepsilon$ is the visible area of the light source.

2.2.2 Lighting quality

The lighting quality is assessed through factors such as glare and uniformity. These factors are discussed in the subsequent subsections.

2.2.2.1 Glare

Glare is a visual discomfort caused by difficulty seeing in the presence of bright light. Glare is classified into two categories; direct glare and reflected glare. Direct glare is generally caused by luminaires without glare control and very bright surfaces, and reflected glare can be caused by reflective surfaces, incorrect luminaire arrangement, or incorrect workstation position [21]. The main effects of glare on users are fatigue or eye strain, and loss of concentration.

2.2.2.2 Light uniformity

Light uniformity is a measure of how uniform or even the light levels are in an area. Light uniformity is calculated as the ratio between minimum to average lux, or minimum to maximum lux.

$$\text{Lighting uniformity} = \frac{E_{min}}{E_{average}} \qquad \text{or} \qquad \frac{E_{min}}{E_{max}}. \tag{2.3}$$

The EN12464 standard [22] requires a certain task to be provided with a certain uniformity of lighting. For general lighting applications, the illuminance uniformity ranges between 0.4 and 0.6.

2.3 ARTIFICIAL LIGHT SOURCE

Artificial light sources are referred to as electric light devices that produce visible light from electric currents. To fully comprehend different types of electric light sources, the subsequent subsections discuss existing electric lights.

2.3.1 Electric lights classification

Depending on light production, electric lights are classified into three categories: (1) incandescence; (2) gas-discharge; and (3) electro-luminescence. The composition of each classification is depicted in Figure 2.2.

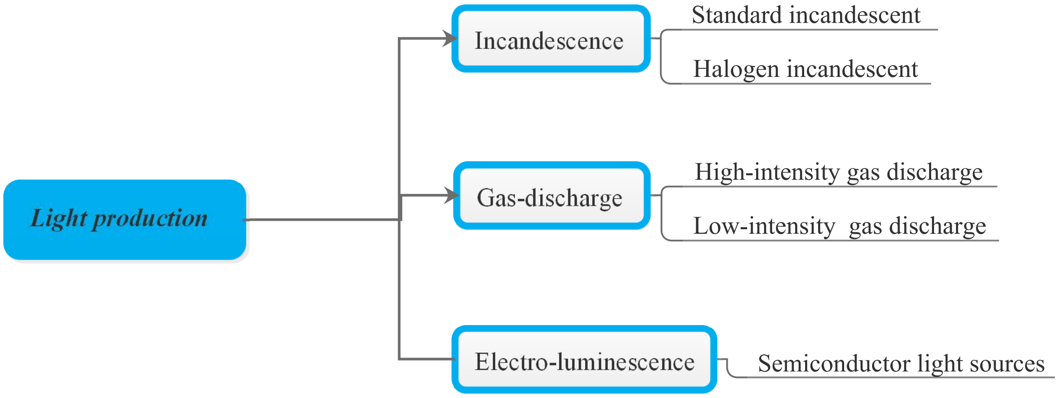

Figure 2.2. Electric lights classification.

2.3.1.1 Incandescent lamps

Incandescent lamps use incandescence to produce light. Incandescent lamps are grouped into three categories: (1) standard incandescent (least efficient), (2) halogen lamps (more EE than standard ones), and (3) reflector lamps (used mainly for floodlighting, spotlighting, and down-lighting applications for both indoor and outdoor applications). Compared to other existing lamps, incandescent lamps are the most inefficient lamps; 90% of the electric energy goes to heat and only 10% produces visible light. They have a very short lifetime (between 1 000 h and 4 000 h), low efficacy, and high operating cost. Incandescent lamps are resistive loads and do not draw any reactive power [23], thus their power factor (Pf) is close to 1. The luminous efficacy of incandescent lamps ranges between 9 lm/W and 12.6 lm/W. In different countries, regulations have been developed and adopted to phase out incandescent bulbs in favour of EE lighting alternatives.

2.3.1.2 Gas-discharge lamps

Gas-discharge lamps are the type of electric lights that produce light by creating an electrical discharge between two electrodes inside the transparent tube filled with ionized gas [24]. Gas discharge lamps do not work by simply connecting them directly to the main circuit. Operating a gas discharge lamp is only possible in combination with control gear. Modern control gear has integrated functions that ignite the lamp and limit the amount of current in the electrical circuit by means of a driver. There are two main types of gas-discharge lamps [25]:

- *High-intensity gas discharge (HID) lamps*: Concerning HID lamps, three concepts can be identified, which are high-performance lamps (HPL) that are based on mercury; sodium (SON) lamps that are based on sodium; and metal-halide (MH) lamps. In the HID lamp, the light is generated via direct radiation from the gas discharge. The quality of light depends on the element used. SON lamps typically radiate yellowish light and are mainly used for functional outdoor lighting. HPL and MH lamps produce white light. Because of poor energy efficacy, HPL lamps are to be banned in the coming years. MH lamps, especially the ceramic type, are very popular, as they combine high energy efficacy with perfect colour performance.
- *Low-intensity gas discharge lamps*: The two most well-known types of low-pressure discharge lamps are fluorescent lamps and compact fluorescent lamps (CFLs). In a fluorescent lamp, a tube is filled with a small amount of mercury gas. These lamps typically generate ultra-violet radiation and some blueish light. By applying a phosphor layer the ultra-violet radiation is converted to visible light. The luminous flux of fluorescent lamps depends on their operating conditions and ambient temperature.

2.3.1.3 Electroluminescent lamps

Electroluminescent lamps emit light when an electric current is passed through them, or when subjected to a strong electric field. The most commonly known electroluminescent lamps are LEDs. LEDs are diodes. A diode has a P-N junction across which charge carriers such as electrons and holes pass when current flows through the diode. When forward-biased, the electrons from the N region flow to the P region and the holes from the P region towards the N region. Some of the electrons recombine with the holes at the junction and their energy is radiated outward. The type of material and process of creating

N-type and P-type determine the colour of the photon as well as the efficiency and other performance characteristics of LEDs. Figure 2.3 shows the working principle of an LED.

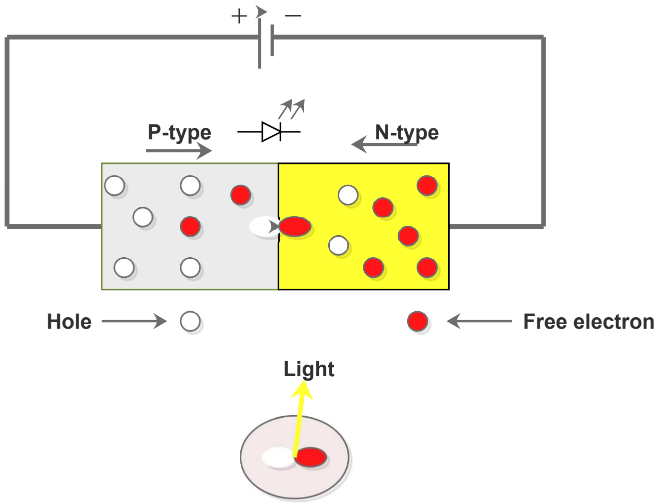

Figure 2.3. Working principle of an LED.

LEDs are used in different areas including mobile appliances, computer monitors, and general illumination (indoors and outdoors). Compared to traditional lighting, LEDs offer different advantages, including high efficiency, good physical robustness and compactness, a long lifetime (15 000 h - 100 000 h), high luminous efficacy, and being easily dimmable.

LEDs are equipped with electrical circuits or drivers that supply current to light the LEDs based on the required brightness to prevent damaging it. LEDs that typically require an external driver include cove lights, down-lights, and tape lights, which are usually used for commercial, outdoor, or roadway lighting applications. External LED drivers are grouped into two types [26]: constant-current drivers (regulate output to provide constant current) and constant-voltage drivers (regulate output to provide constant voltage). Figure 2.4 shows the LED light bulb components.

2.3.2 Characteristics of electric lights

Electric lights are characterized by five main factors, namely lumen efficacy, colour temperature, lifetime, CRI, and Pf.

(i) *Luminous efficacy*

Luminous efficacy (η) is defined as the ratio of lumen output ($\phi_{\text{light ouput}}$) to the power required

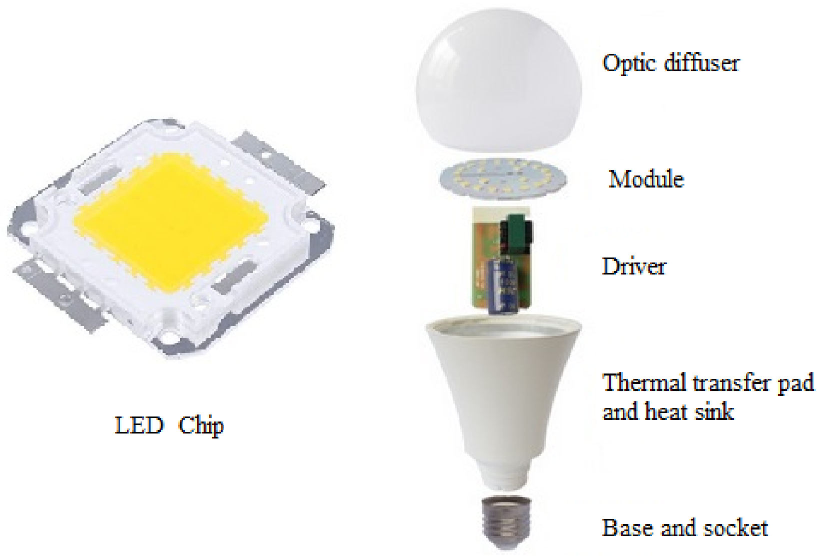

Figure 2.4. LED light bulb components.

by a lamp (P_{input}). η is given in lumens per watt (lm/W).

$$\eta = \frac{\phi_{\text{light ouput}}}{P_{\text{input}}}. \tag{2.4}$$

(ii) *Colour temperature*

Colour temperature (CT) describes the light appearance provided by a light bulb. It is measured in degrees Kelvin (K). The three primary types of colour temperature for the light source as presented in Table 2.1 are soft white, bright white/cool white, and daylight. The higher the degrees, the whiter the colour temperature.

Table 2.1. Light colour temperatures and their associated light appearance and applications.

Colour temperature	Light appearance	Application
Up to 3 300 K	Soft/warm white	Bedrooms and living rooms
3 300 - 5 300 K	Bright/cool white	Kitchens, bathrooms or garages
From 5 300 K	Daylight	Bathrooms, kitchens and basements

(iii) *Lifetime*

The lifetime (L_f) of an electric light source is defined as the time of use before the electric light fails. It is measured in hours.

(iv) *Power factor*

The Pf is technically defined as the power used (Wattage) compared to the total power supplied by the utility (Volt-ampere)[1]. The Pf determines how efficiently an electrical or electronic product utilizes its power. The range of Pf is a decimal between 0 and 1. Utilities use the Pf when evaluating lighting products. Generally, power means the product of voltage and current ($V \times I$), but in an alternative current (AC) circuit, except for a pure resistive circuit (e.g. incandescent bulbs and heating elements), there is usually a phase difference between voltage and current, thus VI does not give real power or true power in the circuit. This phase can take two basic forms [2]: (1) the current can lag behind the voltage when an inductive load is used, or (2) the current can lead when a capacitive load is used. An electrical circuit containing a dominantly resistive load has a Pf of almost 1 and the Pf of inductive and capacitive loads is less than 1. The relation between active power/real power (a power that is consumed or utilized in an AC circuit), reactive power (a power that is constantly oscillating between load and source) and apparent power (the combination of reactive power and active power) is shown in Figure 2.5 using a power triangle.

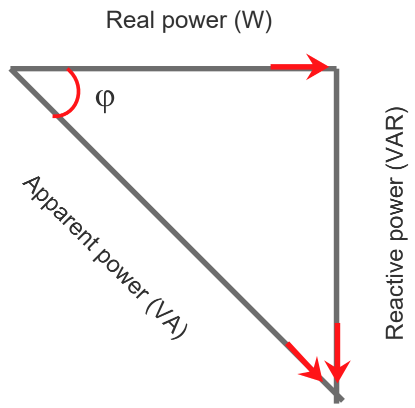

Figure 2.5. Power triangle.

From the power triangle the Pf and apparent power (power supply by the utility) can be calculated as

$$Pf = \cos\varphi = \frac{Pr}{Ps}, \tag{2.5}$$

[1]https://www.nottingham.ac.uk/etc/pdfs/PowerFactor.pdf

[2]http://www.eaton.com/ecm/groups/public/ 40pub/40electrical/documents/content/sa02607001e.pdf

$$Ps = \frac{Pr}{Pf}\,, \tag{2.6}$$

where Pr is the reactive power (in kW), Ps is the power supply by the utility (in $kVAR$), and Pf is the Pf.

The Pf of CFLs and LEDs vary depending on the type of ballast and driver load (inductive or capacitive) used. The Pf was not an issue in the days when all bulbs were resistive incandescent since they naturally had a Pf close to 1. However, when CFL and LED-based lighting fixtures replace incandescent and halogen ones, the Pf is taken into consideration. A comparative analysis of electric light source characteristics is presented in Table 2.2.

Table 2.2. Comparison of electric light sources characteristics.

Electric light source	η	CT	L_f	CRI	Pf
Standard incandescent	9-12.6 lm/W	3 200 K	1 000-2 000 h	> 95	1
Halogen	16-24 lm/W	3 200 K	1 000-4 000 h	>95	1
Fluorescent	50-70 lm/W	2 700-5 000 K	6 000-15 000 h	>80	0.5-0.9
CFL	50-100 lm/W	2 700-5 000 K	8 000-20 000 h	>80	0.5-0.9
LEDs	>70 lm/W	2 700-5 000 K	15 000 -100 000 h	65-95	0.55-0.98

2.4 LIGHTING SYSTEM DESIGN

Lighting system design is a strategic approach to achieve an ideal illumination level with minimum operating costs. The lighting system design process is presented in Figure 2.6. The figure highlights the important steps required in the design of the electrical lighting system and each step is further explained.

Step 1 : *Identify the lighting requirements*

The first step in lighting design is to identify what the lighting installation is intended to achieve.

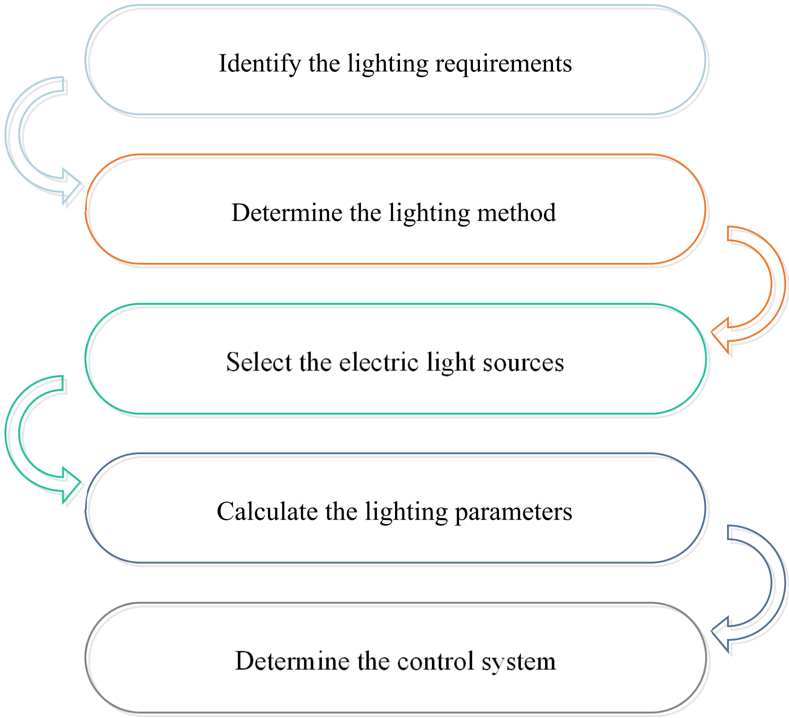

Figure 2.6. Lighting system design process.

This includes the required illuminance, mood of the space, direction of light, and interaction with daylight. There are international recommendations that specify the light level required to provide good visual comfort for various tasks and locations. Table 2.3 presents the Chartered Institution of Building Services Engineers (CIBSE) illuminance level recommendations for office and residential buildings.

Step 2 : *Determine the method of lighting to be used*

How the light is to be delivered should be taken into account. Light can be recessed, surface-mounted, direct, indirect, or up-lighting.

Step 3 : *Select the electric light source*

After selecting the method of lighting, the most appropriate lights and luminaires can be chosen. When choosing the light source, attributes such as light output, wattage, efficacy, lifetime, and colour characteristics should be analysed.

Step 4 : *Calculate lighting parameters*

Parameters such as illuminance level and the number of required lamps are calculated to meet the initial requirements. Methods such as three-dimensional modelling and manual calculation methods can be used to calculate lighting parameters. The three-dimensional modelling method

Table 2.3. CIBSE illumination level recommendations for office and residential buildings.

Office	Recommended illumination level	Residential	Recommended illumination level
General	500 lux	Toilets	100 lux
Computer workstations	300-500 lux	Bathrooms	150 lux
Filing rooms	300 lux	Bed-head	100 lux
Print rooms	300 lux	Desk	150 lux
Drawing office	500 lux	Kitchen	200 lux
Drawing boards	750 lux	Dining	150 lux

estimates the lighting parameters using lighting calculation computer programs such as DIALux, AGi32, Relux, DL-Light, etc. In contrast to the three-dimensional modelling method, the manual calculation method uses mainly the lumen method [3] to calculate the lighting parameters. The lumen method determines the average light level in open areas or rooms. By using the lumen method, the average illumination level and number of lamps required in a given room to provide the required illumination level are mathematically expressed as

$$E_{av} = \frac{\phi_0 \times n \times LLF \times UF}{A_r}, \tag{2.7}$$

$$n = \frac{A_r \times E_{av}}{\phi_0 \times LLF \times UF}, \tag{2.8}$$

where E_{av} is the average illuminance (in lx) in the room, n is the number of lamps required, ϕ_0 is the initial bare lamp flux (in lm), LLF is the light loss factor, UF is the utilization factor, and A_r is the area of the room (in m^2).

Step 5 : *Determine the control system*

The efficiency of a lighting system is also affected by the control system chosen. Consideration should be taken of how switches can be selected and used efficiently, and the possibility of using light controls.

[3] http://personal.cityu.edu.hk/ bsapplec/lumen.htm

2.5 LIGHTING RETROFITTING

Retrofitting is referred to as the modification of a system to improve energy efficiency [27]. From the lighting point of view, retrofitting is the practice of upgrading the existing light fixtures or lamps to reduce energy consumption and increase lighting quality. Figure 2.7 presents the main strategies used to achieve lighting retrofitting goals.

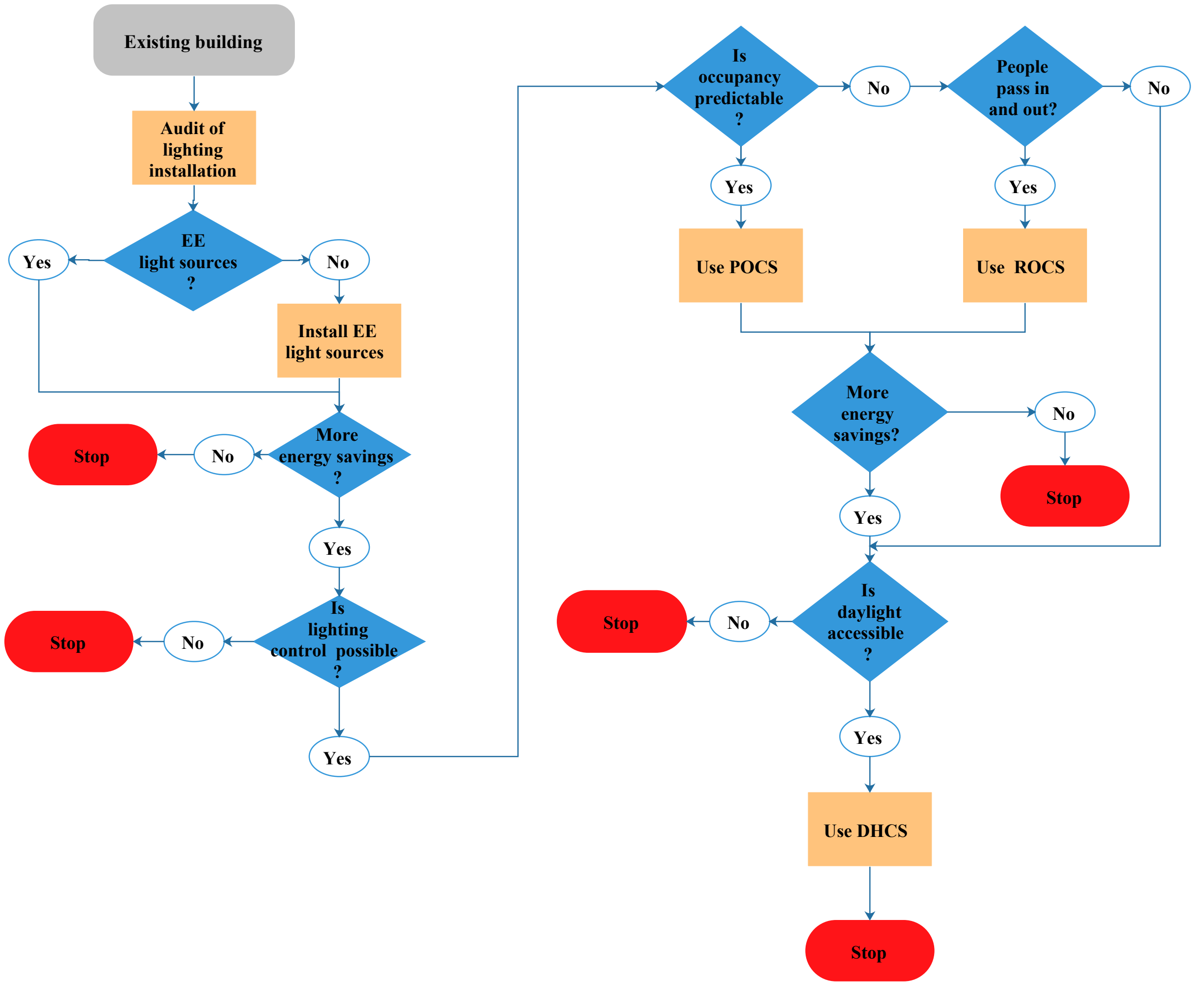

Figure 2.7. Lighting retrofitting strategies for existing buildings.

2.5.1 Lighting retrofitting strategies

To achieve the goals of lighting retrofitting projects, different strategies exist, depending on building characteristics, projects budget, and usage patterns. The most commonly used lighting retrofitting strategies are energy efficiency and lighting control strategies.

2.5.1.1 Energy efficiency strategy

An energy efficiency strategy uses the approach of providing the right amount of light using less energy. To achieve this, inefficient lights are replaced by EE lights. In the last decades, incandescent lamps and linear fluorescent lamps such as standard T8 lamps were the dominant light source in most residential and office buildings because they were one of the most efficient light sources with a decent lifespan available on the market. Nowadays, these light sources are outdated and need to be replaced. Tables 2.4 and 2.5 present the alternative EE lights to incandescent lamps and standard T8 fluorescent tubes, respectively.

Table 2.4. Alternative EE lighting lamps to standard and halogen incandescent lamps.

Traditional lighting		EE lighting alternatives		
Standard incandescent	Halogen	CFL	LED bulb	Lumen range
12 - 15 W	-	-	1 W	-
25 W	25 W	5 - 6 W	4 W	210 lm
30 W	30 W	7 - 9 W	5 W	280 lm
40 W	35 - 40 W	9 - 13 W	7 - 9 W	380 - 450 lm
60 W	45 - 50 W	13 - 15 W	10 W	500 - 800 lm
75 W	60 W	18 - 23 W	12 W	1100 lm
100 W	70 W	25 - 30 W	15 W	1500 lm
150 W	-	30 - 52 W	25 W	2600 lm

Table 2.5. Alternative EE lighting lamp to fluorescent lamp.

Fluorescent tube	LED tube	Lumen range
70 W	24 W	1900 - 3000 lm
58 W	22 W	1600 - 2800 lm
35 W	18 W	1200 - 2600 lm
20 W	9 W	800 - 1600 lm

2.5.1.2 Lighting control strategy

While an energy efficiency strategy provides the right amount of light using less energy, lighting controls are used to distribute the exact illumination level required. Depending on their application, lighting control strategies can be divided into four main categories [28, 29, 30]:

(i) *Predicted occupancy control strategy (POCS)*

A POCS generates energy savings by reducing the operating hours of lighting installation. Lights are turned on/off according to a pre-set daily time. Schedules generally change daily in accordance with the occupancy of the building. By automatically switching off lights at a pre-set time, the system helps to prevent lights from being lit when the building is not occupied. The POCS is mainly applied in situations where building occupancy patterns can be predicted.

(ii) *Real occupancy control strategy (ROCS)*

For the ROCS, the system switches the lights on when the room is occupied and off when is not occupied. The ROCS is used when occupancy is not predictable.

(iii) *Constant illuminance control strategy (CICS)*

The CICS considers the degradation of the lumen output over time. At the design stage, the lighting system is oversized by introducing the maintenance factor. The CICS uses light sensors to measure the light level within a space. If the light level is higher than the required level, the lighting system's controller reduces the lumen output of the lights. If the lumen output is not able to provide the required light level, the lights are replaced by new ones.

(iv) *Daylight harvesting control strategy (DHCS)*

The DHCS is used in areas where daylight is accessible. The DHCS harvests daylight to reduce lighting energy usage. If the daylight is enough to meet the required light level, the lighting system's controller switches off the lights. If the daylight is not enough to meet the required light level, the lighting system's controller dims the lights to compensate for the daylight.

2.5.2 Lighting retrofitting savings determination

After implementing the lighting retrofit project it is necessary to determine savings to validate the project's cost-effectiveness. The energy savings achieved by lighting retrofitting are generally verified by using the measurement and verification (M&V) approach. The M&V method quantifies the energy consumption before and after an energy efficiency measure is implemented to verify and report the energy savings achieved. Several existing protocols provide useful information on M&V. The most common protocols are the International Performance Measurement and Verification Protocols (IPMVP) volume 1, Federal Energy Management Program (FEMP) M&V guidelines version 2.2, and ASHARE guideline 14 [31]. Both the IPMVP and FEMP guidelines were developed by the US Department of Energy. The FEMP M&V guidelines version 2.2 was developed based on the IPMVP targeting the modifications in government buildings. These protocols primarily present the same approaches, which are calibrated simulation, the entire site, and retrofit isolation (more details on the approaches can be found in [31]). The IPMVP provides a more general approach and structure, and ASHARE complements the IPMVP in being more technical. The IPMVP defines energy savings as [31]

$$\text{Energy savings} = (\text{Baseline energy use}) - (\text{Post-installation energy use}), \tag{2.9}$$

where the baseline defines the scenario before the retrofit and the post-installation period is referred to as the scenario after the retrofit. The main M&V activities for lighting retrofit projects are discussed in the following subsections.

2.5.2.1 M&V activities for lighting retrofit projects

The following are the main M&V activities carried out during lighting retrofitting projects:

(i) *Site selection and set-up*

When assessing lighting system performance, the test site should provide stable conditions before and after the retrofit, and the lighting system should be in a stable operating condition before and after the retrofit. Conditions such as a change in occupants, occupant tasks and schedules, should be carefully considered or an alternate site should be chosen.

(ii) *Instrumentation*

Consistent and accurate instruments are important for energy use measurement. Highly accurate measurement instruments are recommended to achieve accurate energy data.

(iii) *Energy use measurement*

The measurement of energy use involves the installation of energy-monitoring equipment. Energy use measurement can be accomplished by using two methods: (1) measuring the entire power circuit system that serves the entire project area (total circuit measurement method), and (2) measuring a sample of representative space types, fixtures, or individual circuits within the project area (sampling measurement method). The first method measures the energy consumption of the complete project without relying on estimates from a few example spaces to generate a project total, while the second method involves measuring the energy use of a representative sample of the spaces in a project and using these data to extrapolate to the energy use of the entire project or the potential energy use in future projects.

(iv) *Light level measurement*

To ensure the effectiveness of the lighting retrofit project for users, the illumination level should be monitored. The following protocols are applicable to ensure accurate and representative light level data: i) only the light being provided by the lights being tested is measured; ii) measurements are recorded at a typical office desk height (0.76 m) for indoor tasks and on the ground or floor surface for outdoor tasks; iii) the same calibrated lux meters are used to minimize the differences in accuracy and internal meter spectrum correction characteristics; iv) temporary obstructions such as materials and furniture are moved before taking measurements, and v) measurements are scheduled and taken after sunset to avoid daylight disturbance.

2.5.3 Existing studies conducted on lighting retrofitting

Various studies have been conducted to develop effective lighting retrofit plans and quantify the benefits of lighting retrofit projects. Reported studies on retrofits focused mainly on analysing energy savings, operational costs, and visual comfort. Table 2.6 presents some of the studies conducted on lighting retrofitting. Retrofitting strategies, the case study used, and the analysis metric are given in detail in this table.

Table 2.6. Some of research conducted on lighting retrofitting.

Retrofitting strategy	Application	Analysis metric	Reference
Lighting controls	Academic building	Energy consumption	[5]
Lighting controls	Office building	Lighting cooling and total electrical energy consumption	[32]
EE lighting	Hotels	Energy consumption	[33]
Lighting controls	Office building	Visual comfort and lighting energy consumption	[34]
EE lighting	Academic office	Energy consumption and light level	[35]
EE lighting	General lighting	Equivalent annual costs	[4]
EE lighting	Academic building	Energy saving, life cycle cost analysis and payback period	[36]
EE lighting and lighting controls	Academic building	Electrical demand and visual comfort	[37]
Lighting controls	Office buildings	Electrical lighting consumption	[28]
EE lighting and lighting controls	Restaurant	Energy, environmental, and cost issue	[38]
Lighting controls	Office building	Energy savings	[39]
Lighting controls	Office building	Energy savings	[40]
Lighting controls	Office building	Energy savings	[41]
EE lighting	Residential building	Energy saving, cost-benefit analysis, and emission reduction	[42]
Lighting controls	Office building	Electricity consumption and illumination level	[43]
Lighting controls	Commercial building	Energy and cost savings	[44]

2.6 ELECTRIC LIGHTS FAILURE MODES AND MODELLING

2.6.1 Electric lights failure modes

The failure mode is referred to as how an item failure occurs. In the lighting system, failure is declared when a lighting system is unable to meet the design requirements. The most common failure modes of electric lights, as shown in Figure 2.8, are a catastrophic failure, also called burnout failure and degradation failure.

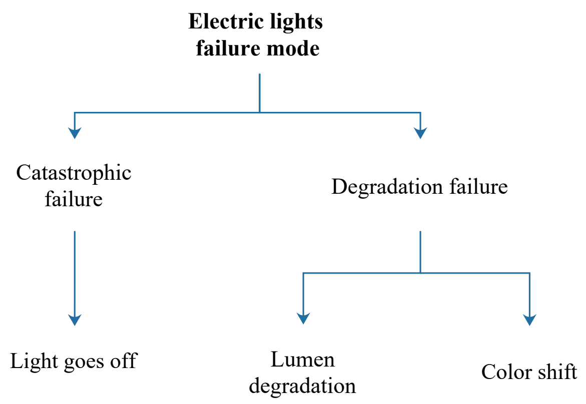

Figure 2.8. Failure modes of electric lights.

2.6.1.1 Burnout failure mode

Burnout/catastrophic failure mode in electric lights is mainly due to faulty materials, deviations in the manufacturing process, or improper handling and operation by the customer [45]. When catastrophic failure happens, the light suddenly goes off.

2.6.1.2 Degradation failure mode

Degradation or wear-out failure mode is based on increased wearing and ageing of the material [46]. The wearing-out process is measurable and referred to as degradation. The most common degradations for electric lights are light output degradation, also called lumen degradation and colour shift.

Lumen degradation

Lumen degradation is referred to as the natural decrease of light output, which happens as the lamp functions over time. The rate and causes of lumen degradation differ from one lighting technology to another. For LEDs, light output degradation depends on different factors, including the LED package and the system materials, and operating conditions such as temperature and driving current [47]. The degradation mechanism is accelerated when LEDs are operated at higher junction temperature than required. Because of their longevity, catastrophic failure is not significant in LEDs. ASSIST defined the lifetime of LEDs as the expected operating hours until the light output has depreciated to 50% of the initial level (for display applications) or 70% (for general lighting application) at room temperature [48].

Colour shift

Degradation failure can also occur in the form of a colour shift. Colour shift is referred to as a change of the original colour. The colour shift occurs in traditional lighting technology as well as in LEDs but has gained more attention related to LEDs owing to their longevity. The colour shift in LEDs is mainly influenced by junction temperature. The colour shift can be a temporary failure due to operating conditions or a permanent failure due to physical changes in LED packages [49]. Currently, there is no agreement on acceptable levels of colour shift (more details on colour shift can be found in [8, 49, 50].

2.6.2 Electric light failure modelling

Electric light failures are modelled based on failure modes. Based on the aforementioned failure modes, electric light failure models are grouped into two main categories: burnout failure models and degradation failure models.

2.6.2.1 Burnout failure modelling

Different models have been developed to predict the surviving population based on burnout failure, including:

(i) *Exponential decay model*

This model quantifies growth or decay at a rate proportional to the population size [51], such as

$$\frac{dN(t)}{dt} = kN(t), \tag{2.10}$$

where $N(t)$ is the population size surviving at time t. Model (2.10) is described as the law of natural growth if $k > 0$, and as the law of natural decay if $k < 0$. The solution to (2.10) is an exponential function given as

$$N(t) = N(0)\ e^{kt}, \tag{2.11}$$

where $N(0)$ is the size of the initial population.

(ii) *Linear population model*

A linear population model is suggested in the AMS-II.J CDM guideline [52]. The linear population model is given as

$$N(t) = \begin{cases} N(0) - t \times H \times \frac{100-y}{100 \times L}, & \text{for } t \times H < L, \\ 0, & \text{for } t \times H \geq L, \end{cases} \tag{2.12}$$

where L is the average lifetime of lamps (h), H is the number of operating hours per year (h), and y is the percentage of surviving population at the end of the average lifetime.

(iii) *Regression analysis model*

The regression analysis model has been proposed to fit the Polish Efficient Lighting Project (PELP) data [53]. The regression analysis model is expressed as

$$N(t) = \frac{1}{1+\ e^{t-L}}. \tag{2.13}$$

Model (2.13) is similar to the logistic population model proposed by Verhulst [54], given as

$$N(t) = \frac{1}{1+\ e^{-t}}. \tag{2.14}$$

(iv) *Improved model of (2.13)*

Carstens *et al.* [55, 56] proposed an improved model of the model (2.13) given as

$$N(t) = \frac{1}{c + e^{bt-L}}, \tag{2.15}$$

where c and b are the initial value and slope parameters, respectively. The discrete dynamic form of (2.15) is given as

$$N(t+1) = bcN(t)^2 - bN(t) + N(t). \tag{2.16}$$

2.6.2.2 Degradation failure modelling

1. *Lumen degradation*

   Different models have been developed to calculate and predict the lifetime of LEDs based on light output degradation. These models are mainly derived from two methods, the TM-21 method and the accelerated test method. The TM-21 method is recommended by the Illuminating Engineering Society (IES) for predicting the lumen degradation of LEDs based on data collected according to the LM-80 standard. LM-80 is the approved method for measuring lumen maintenance (a measurement used to evaluate the decrease in light output of a lamp that occurs over time) of LED packages, arrays, and modules at various temperatures [57]. The TM-21 method has been adopted by most top LED tier manufacturers, including Philips and Osram. The accelerated test method is based on testing the lumen degradation and the useful lifetime of an LED light source by subjecting LED to operating conditions above its normal service parameters.

   (a) TM-21 method

   This method is implemented as follows:

   * *Selecting the sample size*: In the TM-21 method, the sample size required for modelling is estimated based on the LM-80-08 testing standard. In this standard, the minimum sample size recommended is 20 to project six times of test duration, and 10 to 19 samples to project 5.5 times the test duration.
   * *Luminous flux data collection*: After selecting the sample size, the luminous flux of sample tests are collected at intervals of 1 000 hours for a test duration of 6 000 hours. Collected data are normalized to 1 at time zero test point, and the normalized measured data are averaged.
   * *Curve-fit*: The non-linear least square (NLS) method is used to fit the averaged measured data. The results indicated that the lumen degradation data followed the

exponential curve as

$$\phi(t) = \alpha\, exp\big(-\beta t\big), \tag{2.17}$$

where $\phi(t)$ is the luminous flux (in lm) at time t, α is the initial luminous flux (in lm), and β is the degradation rate.

* *Projecting lumen maintenance life*: Lumen maintenance life (L_f) is defined as the elapsed operating time (in hours) at which the specified percentage of lumen depreciation (lumen maintenance) is reached. L_f is expressed as

$$L_f = \frac{\ln\left[\frac{100\times\alpha}{Lp}\right]}{-\beta}, \tag{2.18}$$

where Lp is the maintained percentage of the initial lumen output. Figure 2.9 depicts the lumen maintenance of LUXEON LED Lumileds Philips of initial lumen output of 80 lm under different lumen degradation rates.

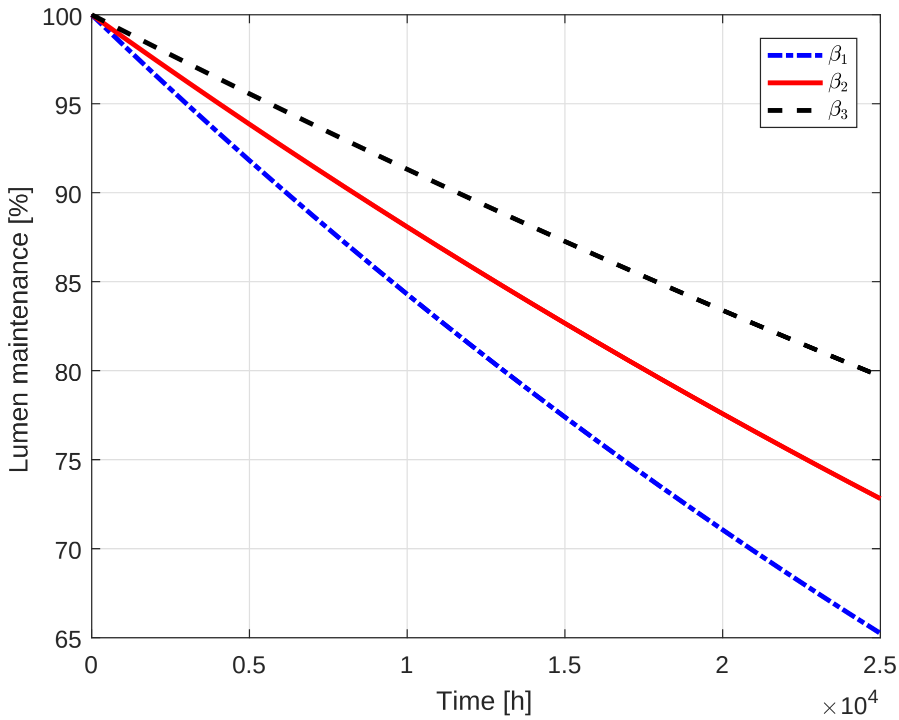

Figure 2.9. Lumen maintenance using (2.18) under different degradation rates; $\beta_1 = 1.708\times 10^{-5}, \beta_2 = 1.269\times 10^{-5}, \beta_3 = 0.908\times 10^{-5}$.

For the TM-21 method, tested units are characterized by the same degradation rate β. This means the variance of each test unit is not considered. This may result in insufficient reliability information about the products. In this regard, different stochastic models have been developed to predict the time to failure of samples by considering their variances. In stochastic models, the degradation rate of each test unit is calculated and the statistical properties of degradation rates are analysed to determine the time to failure. Distributions such as two-parameter Weibull, two-parameter exponential, and two-parameter log-normal [58] have been used to calculate the time to failure of LEDs. Stochastic models follow TM-21 procedures except that the degradation rate of each unit is estimated instead of using the average.

For stochastic models, the cumulative probability of failure distribution is used to estimate time to failure. The cumulative probability of failure distribution $F(t)$ is expressed as

$$F(t) = P[\varepsilon \leq t], \tag{2.19}$$

where ε is the lifetime of a LED (hours of use before LED fails). By using (2.18), ε can be expressed as

$$\varepsilon = \frac{\ln\left[Lp\right]}{-\beta}; \tag{2.20}$$

substituting (2.20) in (2.19)

$$F(t) = P\left[\frac{\ln\left(Lp\right)}{-\beta} \leq t\right]. \tag{2.21}$$

(b) Accelerated test method

LEDs have a long lifetime (15 000 h - 100 000 h); it is not practical to gather data over the whole lifetime. For this reason, an accelerated test method is used to predict LED lumen degradation and lifetime. In the accelerated test method, the lifetime obtained under stress conditions is multiplied by the acceleration factor to obtain an estimated lifetime under nominal operating conditions. Lifetime under normal operating conditions is expressed as

$$\varepsilon = \varepsilon' A_f, \tag{2.22}$$

where ε' is the lifetime under stress (in hours), and A_f is the acceleration factor.

Lumen degradation is mainly accelerated by operating and environmental conditions such as temperature, forward current, and humidity. In the literature, acceleration factor models have been formulated based on temperature, forward current and humidity.

The acceleration factor for temperature stress conditions is expressed using the Arrhenius model as [18]

$$A_f = e^{\frac{-E_{act}}{k_b}\left(\frac{1}{T_1} - \frac{1}{T_0}\right)}, \tag{2.23}$$

where A_f is the acceleration factor, k_b is the Boltzmann constant (8.617385 $\times 10^{-5}$ eV/K), E_{act} is the activation energy (in eV), and T_1 and T_0 are the operating temperatures (in K) under excess and normal conditions, respectively.

For forward current and temperature stress conditions, the acceleration factor is expressed as [59]

$$A_f = \left(\frac{I_0}{I_1}\right)^{-\zeta} e^{\frac{-E_{act}}{k_b}\left[\frac{1}{T_1}-\frac{1}{T_0}\right]}, \tag{2.24}$$

where ζ is a coefficient of the luminous flux effect over the device lifetime, and I_0 and I_1 are the forward currents (in A) under normal and stress conditions, respectively.

For temperature and humidity stress conditions, the acceleration factor is expressed using the Peck model as [60]

$$A_f = \left(\frac{H_0}{H_1}\right)^{m} e^{\frac{-E_{act}}{k_b}\left[\frac{1}{T_1}-\frac{1}{T_0}\right]}, \tag{2.25}$$

where H_0 and H_1 are the relative humidity (in percentage) under normal and stress conditions, respectively.

2. Colour shift

   The colour shift over time is complex; to date no standards for projecting colour shift have been formulated. The direction of colour shift can vary over time, which creates uncertainty not only in the direction of the shift, but also in magnitude. IES has formed a team working on developing a standard for projecting long-term chromaticity shifts, which will be called TM-31 [61].

2.6.2.3 Existing studies conducted on lighting failure modelling

Burnout models discussed in Subsection 2.6.2.1 have been applied in different studies. Model (2.12) has been applied in [62] for optimal sampling design for the purpose of M&V. Model (2.16) has been applied in studies [63, 64] to design a maintenance plan for EE lighting retrofit projects, and in reference [65], it is used in the formulation of optimal M&V metering plans for EE lighting retrofit projects.

In the literature, degradation failure models are developed based on lumen degradation, especially for LED lighting systems. Table 2.7 presents different studies that developed models to predict lumen degradation and the lifetime of LEDs.

Table 2.7. Different studies conducted on lumen degradation and lifetime estimation of LEDs.

Basis method for model	Model	Analysis factor	Reference	Year
TM-21	Particle filtering	Lifetime	[66]	2017
	Statistical model (Log-normal and Weibull)	Lifetime	[67]	2017
	Thermal modelling and temperature measurement	Junction temperature and lumen degradation	[17]	2016
	General degradation path model	Reliability	[58]	2012
Accelerated test method	Accelerated aging test	Lumen degradation	[68]	2018
	Multi-stress based predictive model	Lifetime	[60]	2017
	Electrothermal characteristic based model	Lifetime	[59]	2016
	Exponential decay and Arrhenius	Lumen degradation	[18]	2016
	Step-stress accelerated test	Lifetime	[69]	2015
	Wiener process	Lumen degradation	[70]	2014
	Temperature and humidity experimental model	Lumen degradation	[71]	2013
	Inverse power law	Lifetime	[72]	2012

2.7 LIGHTING SYSTEM MAINTENANCE

Maintenance is referred to as all work (cleaning, repairs, and replacement, etc.) undertaken or required to maintain an item or a system in good and workable production conditions [73]. After identifying a failure, maintenance is necessary to maintain the performance of the equipment/system.

2.7.1 Maintenance approaches

Depending on when maintenance is performed (before or after failure), maintenance activities are grouped into two categories [74]: reactive maintenance/corrective maintenance (CM), and preventive maintenance (PM).

2.7.1.1 Corrective maintenance

CM is the maintenance carried out after an item has failed. During CM, the faulty item or component is repaired or replaced to restore its intended function. CM is done randomly because failure cannot be known a priori. Some of the disadvantages of CM are unpredictability, having to stop operations, and higher long-term costs.

2.7.1.2 Preventive maintenance

PM is the maintenance performed regularly to maintain the item or system in satisfactory operating condition. PM is performed while the item is still working to prevent it from failing unexpectedly. Unlike CM, PM is performed on schedule. PM prolongs the lifetime of equipment, reduces capital replacements and improves the efficiency and the performance of equipment by increasing uptime.

2.7.2 Maintenance processes

Maintenance is generally carried out using six steps, as shown in Figure 2.10.

For lighting systems, these steps are defined as follows:

Figure 2.10. Maintenance process steps.

Step 1: Define function and performance

The functions of a lighting system need to be defined. These functions determine the operation of the system under specified working conditions.

Step 2: Define functional failure

Failure is declared when a lighting system is unable to meet design requirements.

Step 3: Identify the failure mode

The typical failure modes of electric lights, as discussed in Section 2.6.1, are catastrophic failure and degradation failure modes.

Step 4: Determine the effects and consequences of failure

This step determines what will happen if a catastrophic or degradation failure occurs. The effects of the failure on the users, environment, and operational costs are assessed.

Step 5: Select the maintenance approach

Depending on the failure mode identified, the maintenance approach needed to mitigate functional failures can be chosen.

Step 6: Implement and refine the maintenance plan

The maintenance approach selected in Step 5 is implemented and the results are analysed to determine if the lighting system needs to be reviewed to ensure its effectiveness.

2.7.3 Maintenance policies

Based on CM and PM, different policies have been developed to identify an effective maintenance plan. Different policies for single-unit and multi-unit systems are detailed in reference [75].

For single-unit applications, five main policies developed are:

- *Age-dependent PM policy*

  For the age-dependent PM policy, PM is scheduled at a fixed age and CM is performed at failure.

- *Periodic PM policy*

  For a periodic PM policy, PM is set at fixed time intervals regardless of the failure history of the unit, and repairs are carried out in case of failure.

- *Failure-limiting policy*

  For the failure limit policy, PM is carried out once the failure rate of a unit attains the predetermined failure level.

- *Sequential PM policy*

  For the sequential PM policy, PM is carried out at uneven time intervals. Over time, the time intervals become progressively shorter owing to more frequent maintenance with age.

- *Repair-limiting policy*

  For the repair-limiting policy, a failed unit is repaired or replaced depending on the predetermined limit criterion. For example, if the repair cost is considered as a failure criterion, the unit is repaired if the repair cost is less than the set repair cost limit, and this is called a repair cost-limiting policy.

For a multi-unit system, there is a dependency on the multi-component system. The dependency can either be economic dependence or failure dependence. The failure of one sub-system may affect one or more other sub-systems. The following maintenance policies have been developed for multi-unit systems:

- *Group maintenance policy*

  Under the group maintenance policy, components that must be replaced in the event of failure are identified. These categories may be established based on the component's stochastic failure.

- *Opportunistic maintenance policy*

  Under the opportunistic maintenance policy, if maintenance is planned for a certain unit, in the process of performing maintenance of the targeted unit, the maintenance of other units whose maintenance time imminent is carried out at the same time. This results in a reduction in the time and cost of managing maintenance resources. Table 2.8 presents a summary of maintenance policies for single-unit and multi-unit systems.

Table 2.8. Summary of maintenance policies for single-unit and multi-unit systems.

System	Policy	Planning horizon	Action	Reference
Single-unit	Age-dependent PM	Fixed age	Repair and replacement	[76, 77]
	Periodic PM	Periodic time	Repair and replacement	[78, 79, 80]
	Failure limit	Finite or infinite	Repair	[81, 82, 83]
	Sequential PM	Finite	Repair and replacement	[84, 85]
	Repair limit PM	Infinite	Repair and replacement	[86, 87]
Multi-unit	Group maintenance	Fixed age and when failure occurred	Repair and replacement	[88, 89, 90]
	Opportunistic maintenance	Fixed age and at failure	Repair and replacement	[91, 92, 93]

For the lighting system, the CM is carried out to replace the burned-out lamps while the PM actions include a routine cleaning of lamps and luminaire, inspections and repair, and replacement are carried out to maintain the efficiency of a lighting system. The periodic PM policy is the most practical and applied most frequently as it does not involve uneven maintenance intervals, nor needs to record on the use and age of the unit. Periodic PM is performed by replacing failed lamps at a certain maintenance level.

2.7.4 Maintenance optimization

Two main questions are asked to compile an effective maintenance plan. The first question is what type of maintenance policy should be considered, and the second question is when to perform the chosen maintenance to achieve the best results. The first question can be answered after identifying the failure mode of the item and determining the activities needed to restore its intended functions. The answer to the second question depends on factors such as the financial cost and benefits of maintenance. In general, maintenance costs money in terms of material and wages. A survey conducted by Robertson and Jones [94] indicated that the maintenance budget ranged from 2% to 90% of the total system operating budget, with the average being 20.8%. Balance is needed between maintenance benefits and costs, and this is where optimization comes in. Optimization is defined as a method used to solve the conflicts of a decision situation so that the decision variables take the best possible values [12]. The main processes of optimization are discussed in the following subsection.

2.7.4.1 Optimization process

Optimization covers four main processes:

i. *Setting objective*

   The first step in designing a maintenance optimization problem is to determine the objective of the problem.

ii. *Identify design variable*

   Design variables are the parameters that need to be determined to achieve the best optimal solution under given constraints.

iii. *Modelling*

   A model is a description of a system using mathematical concepts and language. The purpose of modelling a system is the development of a scientific understanding of the behaviour of a system under various conditions. [95].

iv. *Obtaining solution from models*

   Mathematical models are mainly solved using two methods: an analytical method and a numerical method. The analytical method uses exact theorems to present formulas. In many maintenance problems, the analytical method is impracticable owing to problem complexity.

Depending on the available information about the states of factors influencing the system, the maintenance optimization model can be classified into three main categories [13]: certainty, risk, and uncertainty. Figure 2.11 presents the classification of the maintenance optimization model based on the degree of certainty.

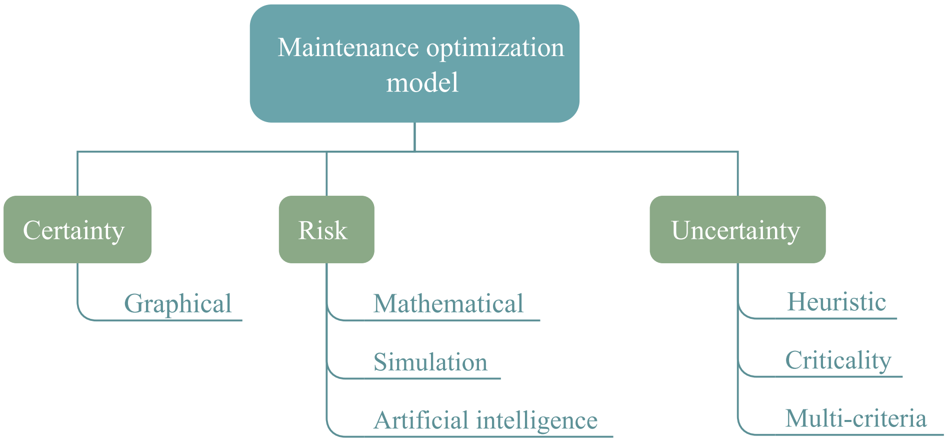

Figure 2.11. Maintenance optimization model.

The certainty model uses a graph or figure to denote an optimal maintenance solution [96, 14]. In the risk model, the states of the influencing factors are known. Based on current information on the states of the influencing factors, future possible conditions can be predicted and can determine a suitable optimal plan. Typical models under the risk model are mathematical models, simulation, and artificial intelligence [97, 98, 99]. Under the uncertainty model, future conditions and their corresponding probabilities are not known. Thus, to accomplish optimization, relevant information usually needs to be ascertained based on judgment and utilization through subjective probabilities. Typical models under uncertainty are heuristic, criticality, and multi-criteria models [100, 101, 102].

2.7.4.2 Existing studies conducted on maintenance optimization

Various studies have been conducted on the maintenance optimization of different systems and items. Table 2.9 presents some of the research conducted on maintenance optimization.

Table 2.9. Some of research conducted on maintenance optimization.

Reference	System	Objective	Criteria considered
[103]	Power system	Optimal maintenance strategy	Risk index
[104]	Offshore wind turbine components	Minimize maintenance cost	Age threshold of components and failure rate
[105]	Office building	Maximize energy savings and internal rate of return	Failure, payback period, and energy savings
[63]	Lighting system	Maximize cost benefit ratio	Energy savings, maintenance cost, and failure
[106]	Unit of chemical plant	Optimal maintenance alternative	Risk of equipment failure and cost maintenance
[107]	Companies	Minimize equipment downtime	Failure
[108]	Factories	Minimize the make-span of the jobs	Reliability
[109]	Infrastructure	Minimize the life cycle cost	Reliability
[110]	Rolling element bearings and pump station	Optimum maintenance	Failure
[111]	Oil companies	Optimum maintenance strategy	Non-monetary factors
[112]	A non-repairable single component and multi-component repairable systems	Minimizing the expected total system cost	Deterioration

2.8 CHAPTER SUMMARY

In this chapter, the background and a literature review on lighting systems design, lighting retrofitting, electric lights failure modes and modelling, and lighting system maintenance are covered. In reported literature on lighting maintenance, periodic preventive maintenance based on replacing failed lamps at a certain maintenance level is the most often applied. The lighting maintenance plan developed in the existing 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. 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. This research focuses on the luminous flux degradation of LEDs caused by the variation of the operating junction temperature owing to the users' lighting level requirements, and lighting maintenance optimization problems that take into account the lumen degradation.

CHAPTER 3 ENERGY-MAINTENANCE OPTIMIZATION FOR RETROFITTED LIGHTING SYSTEM INCORPORATING LUMINOUS FLUX DEGRADATION TO ENHANCE VISUAL COMFORT

3.1 CHAPTER OVERVIEW

This chapter is based on our published work [113], entitled "Energy-maintenance optimization for retrofitted lighting systems incorporating luminous flux degradation to enhance visual comfort". Energy-maintenance optimization that considers luminous flux degradation is studied. The lumen degradation of LED lights is modelled based on the variation in operating junction temperature due to the users' lighting level requirements. The optimization model is formulated to maximize energy savings and minimize maintenance costs. To minimize maintenance costs and maximize energy savings, the number of lamps to be replaced and the brightness dimming level are chosen as the design variables of the optimization problem. To test the effectiveness of the proposed optimal energy-maintenance plan, an existing academic open-plan office at the University of Pretoria (UP) is used as the case study. The optimization problem is solved using the Solving Constraint Integer Program (SCIP) available in the MATLAB interface OPTI toolbox.

3.2 INTRODUCTION

Visual comfort is generally evaluated through lighting quality and quantity characteristics. The degradation of luminous flux affects the lighting quantity and uniformity more strongly. When the luminous flux decreases, the illumination level at the workspace decreases and the uniformity increases. For computer workstations, CIBSE recommends an illumination level between 300 and 500 lux, and uniformity between 0.6 and 0.4. ASSIST has declared 70% lumen degradation as the threshold at which the human eye can detect a reduction in light output, and recommends a 70% lumen degradation threshold to determine the useful life of LEDs for general lighting applications. The existing solution to maintain an adequate illumination level for an LED-based lighting system is to replace LEDs before the lumen output goes below 70% of the initial lumen output. In this chapter, maintenance (replacement of the LEDs) is designed based on lumen degradation and users' lighting level requirements.

Various LED luminous flux degradation models discussed in the literature revealed that the driving current and the operating junction temperature are the major factors that increase or decrease the luminous flux degradation of LEDs. The LED luminous flux degradation models presented in the literature were performed under several specific conditions, including constant driving current and temperature. However, the junction temperature can vary depending on users' lighting level requirements and driving schemes. In this chapter, the luminous flux degradation model of LEDs is formulated based on the variation in the operating junction temperature due to the users' lighting level requirements. The proposed luminous flux degradation model is then used to develop an optimal lighting maintenance plan, which optimizes the lighting system's performance and maintenance costs.

The major contributions of this chapter are as follows:

- The formulation of a luminous flux degradation model that takes into account users' lighting level requirements. This model helps to estimate the luminous flux degradation accurately, following the users' set light levels.
- The formulation of an energy-maintenance optimal model that takes into account luminous flux degradation. This model maximizes energy savings and minimizes maintenance costs. With this model, it is possible to predict when maintenance should be performed, how many times and lamps need to be replaced during maintenance.

3.3 PROBLEM FORMULATION AND MODELLING

3.3.1 Problem formulation

We consider an LED lighting system in a typical open-plan office, as depicted in Figure 3.1. The office is divided into six workstations (S1, S2, S3, S4, S5, and S6) with an equal number of electric light sources. 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 presence of users in the zones is installed in this office. 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). In this office, users in each zone set illuminance levels according to their own lighting level preferences. At the beginning of the installation, LEDs in each zone are dimmed to satisfy the users' set illuminance level, but as time goes by, the luminous flux of LEDs degrade and the targeted illuminance levels in zones may not be satisfied. In order to maintain the users' lighting level requirements, maintenance is necessary. However, the maintenance of lighting devices adds extra investment. The aim of this study is to develop a maintenance plan that optimizes both lighting system performance and maintenance costs. In this chapter, an optimal energy-maintenance plan that optimizes both lighting system performance and maintenance costs while satisfying users' lighting level requirements is developed. To develop an effective lighting maintenance plan, luminous flux degradation is modelled.

3.3.2 Luminous flux degradation modelling

Luminous flux degradation is the main factor used to predict the lifetime of LED lights. The degradation rate is significantly affected by operating and environmental conditions. Thus, the variation in operating conditions may affect the useful lifetime of LEDs. To understand the impact of operating conditions, it is necessary to model the luminous flux degradation. In this chapter, the luminous flux degradation is modelled based on the variation in operating junction temperature due to users' lighting level requirements.

LEDs located in the same workstation are controlled together. Let $d_i(j)$ denote the dimming level of lamps in workstation i at time j, $d_i(j) \in [0,1]$, and $d_i(j) = 1$ for full brightness, and $d_i(j) = 0$ when

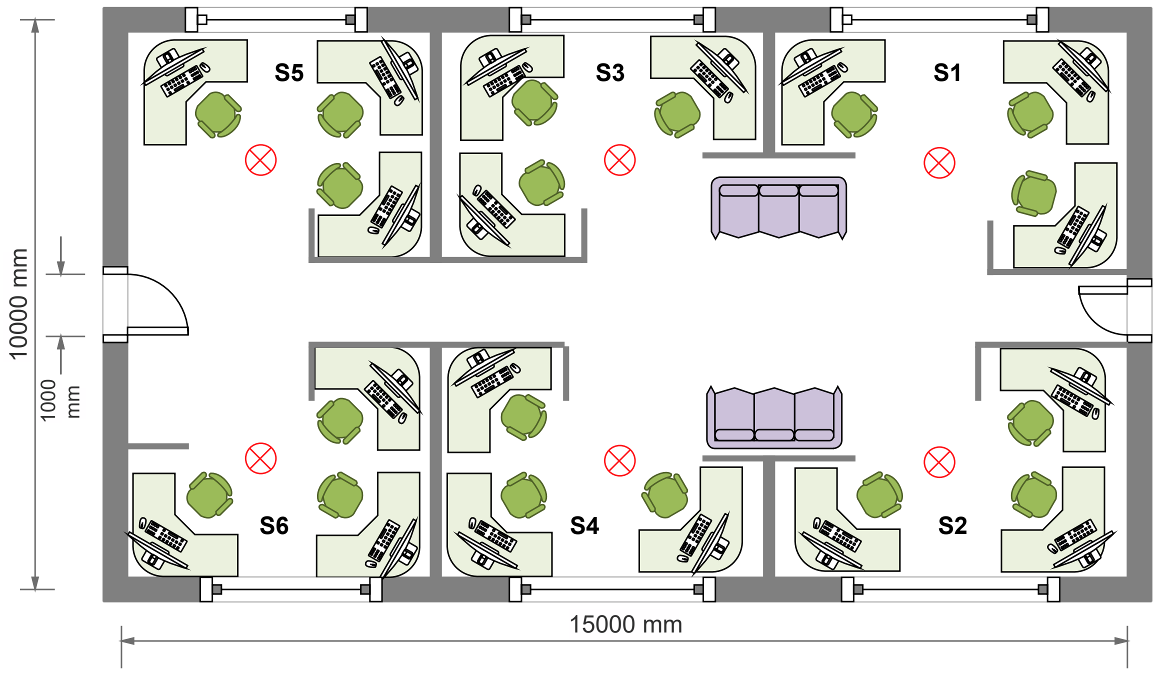

Figure 3.1. Office under study.

lamps are off, $i = 1, 2, \cdots S,\ j = 1, 2, \cdots, K$. User's set illuminance level in workstation i is denoted as $E_{set,i}$. $E_{set,i}$ is constant over the evaluation period.

The measured light level in workstation i at time j is calculated using lumen method as

$$E_i(j) = \frac{n \times \phi_i(j) \times d_i(j) \times U_f \times M_f}{A}\ ,\quad i = 1, 2, \cdots, S,\quad j = 1, 2, \cdots, K, \tag{3.1}$$

where $E_i(j)$ is the light level (in lux) in workstation i at time j, n is the number of LED lights in each workstation, $\phi_i(j)$ is the luminous flux (in lm) of each LED light in workstation i at time j, U_f is the utilization factor, M_f is the maintenance factor, and A is the area (in m^2) of each workstation.

Through luminous flux degradation experimental measurements carried out by IES [10], it was found that the luminous flux degradation of LEDs followed the exponential curve. By using the exponential model $\phi_i(j)$ is calculated as

$$\phi_i(j) = \phi_0\, e^{-\beta_i(j)t_j}, \tag{3.2}$$

where ϕ_0 is the initial luminous flux (in lm), t_j is the operating hours (in h), and $\beta_i(j)$ is the degradation rate of lights in the workstation i at time j.

The degradation rate of lights in the workstations varies with the variation in operating junction temperature. The relationship between the degradation rate and operating junction temperature is expressed using the Arrhenius model [18] as

$$\beta_i(j) = a\, e^{\left(\frac{-E_{act}}{k_b T_{m,i}(j)}\right)}, \tag{3.3}$$

where a is the Arrhenius pre-exponential factor, k_b is the Boltzmann constant (8.617385 $\times 10^{-5}$ eV/K), E_{act} is the activation energy (in eV), and $T_{m,i}$ is the operating junction temperature (in K).

From the thermal model developed in reference [19], the junction temperature can be expressed as

$$T_{m,i}(j) = T_a + P_{heat,i}(j) \times R_{th}, \tag{3.4}$$

where T_a is the ambient temperature (in K), $P_{heat,i}(j)$ is the electricity converted into heat (in W) as in (3.5), and R_{th} is the thermal resistance (in K/W).

$$P_{heat,i}(j) = k_h \times I_F \times V_F \times d_i(j), \tag{3.5}$$

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

The formulated luminous flux degradation model is used to develop an optimal energy-maintenance plan. The optimization problem is formulated in the following section.

3.4 OPTIMIZATION PROBLEM FORMULATION

The luminous flux degradation model is incorporated in the optimization problem to satisfy users' lighting level requirements while optimizing the energy savings and maintenance costs. The optimization problem is formulated in the subsections below.

3.4.1 Design variable

The design variables are referred to as the parameters that have to be determined to achieve the best performance under given constraints. In this optimization problem, the dimming level and the number of lamps to be replaced are the parameters to be determined to optimize both energy savings and maintenance costs.

Assume $m_i(j)$ is the number of lights to be replaced in workstation i at time j. For $i = 1, 2, \cdots, S$, and $t = 1, 2, \cdots, K$. Let $d_i = \left[d_i(1), d_i(2), \cdots, d_i(K)\right]$, $m_i = \left[m_i(1), m_i(2), \cdots, m_i(K)\right]$, $D = \left[d_1, d_2, \cdots, d_S\right]$, and $M = \left[m_1, m_2, \cdots, m_S\right]$. The set of design variables of the energy-maintenance problem over the evaluation period is given as

$$X = \left[D, M\right]^T. \tag{3.6}$$

$d_i(j)$ are continuous values bound between 0 (off) and 1 (full brightness), and $m_i(j)$ are integer values bound between 0 (no replacement) and n (full replacement).

$$\begin{cases} 0 \leq d_i(j) \leq 1, \\ 0 \leq m_i(j) \leq n. \end{cases} \tag{3.7}$$

3.4.2 Objective function

The objectives of the energy-maintenance optimization problem are to maximize energy savings and minimize maintenance costs, which can be formulated into an optimization problem as

$$\begin{cases} \min \quad -ES, \\ \min \quad M_c. \end{cases} \tag{3.8}$$

By using the weighted sum method [114], the optimization problem (3.8) can be expressed as single optimization problem as

$$\min \quad J = -w_1 ES + w_2 M_c, \tag{3.9}$$

where w_1 and w_2 are the weighting coefficients in range $[0, 1]$, and $w_1 + w_2 = 1$. Weighting coefficients are chosen based on the importance given to the attached objective. The higher the weighting coefficient, the more importance is given to the attached objective.

To normalize the objective function (3.9), maximum values of energy savings ($\overline{ES}$) and maintenance costs ($\overline{M}_c$) are used.

$$\min \quad J = -w_1 \frac{ES}{\overline{ES}} + w_2 \frac{M_c}{\overline{M}_c}. \tag{3.10}$$

The energy savings (ES) are referred to as lighting energy saved by installing a lighting control system. It is the difference between lighting energy consumed before and after the installation of a lighting control system.

$$ES = EC_b - EC_a, \tag{3.11}$$

where EC_b is the lighting energy used (in kWh) before the installation of lighting control system, and EC_a is the lighting energy used (in kWh) after the installation of lighting control system. EC_b and EC_a are expressed as

$$EC_b = Pr \times n \times t_{s,b} \times K, \tag{3.12}$$

$$EC_a = \sum_{i=1}^{S} \sum_{j=1}^{K} Pr \times n \times d_i(j) \times t_{s,i}, \tag{3.13}$$

where $t_{s,b}$ is the fixed operating hours before the installation of the lighting control system, and $t_{s,i}$ is the controlled operating hours after the installation of the lighting control system in each sampling interval in workstation i.

The maintenance cost M_c is referred to as the money spent on buying new lighting devices and the replacement of failed lamps with new ones. M_c is expressed as

$$M_c = \sum_{i=1}^{S} \sum_{j=1}^{K} (U_p + L_c) \times m_i(j), \tag{3.14}$$

where U_p is the unit price (R[1]) of a light device, and L_c is the labour cost to replace the light device (R). U_p and L_c are considered constant over the evaluation period.

3.4.3 Constraints

The objective function (3.10) is constrained by the illuminance level required by users, targeted energy savings, and maintenance budget limits.

(i.) *Users' lighting level requirement*

The CIBSE recommends (see Table 2.3), a light level between 300 and 500 lux for computer workstations. The users in workstations can set any light level between 300 lx and 500 lx. The average measured illuminance should be equal to the users' set illuminance level.

$$E_i(j) = E_{set,i}. \tag{3.15}$$

Equation (3.1) can also be expressed as

$$E_i(j) = \frac{\Theta_i(j) \times d_i(j) \times U_f \times M_f}{A}, \tag{3.16}$$

where $\Theta_i(j)$ is the total luminous flux (in lm) of lights in workstation i at time j. $\Theta_i(j)$ is calculated as

$$\Theta_i(j+1) = \sum_{l=1}^{L} \phi_i^l(j)\, e^{-\beta_i \left(T_{m,i}(j)\right) t_{s,i}} + m_i(j)\phi_0\, e^{-\beta_i \left(T_{m,i}(j)\right) t_{s,i}}, \tag{3.17}$$

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

where $L = n - m_i(j)$, and $\phi_i^l(j)$ is the luminous flux of non-replaced lamp l at time (j). $\phi_i^l(j)$ is calculated using (3.2). Failed lamps are replaced by the same type of lamps with the same initial luminous flux and rated power.

(ii.) *Energy savings*

One of the main purposes of installing a lighting control system is to save more energy, but over time the energy savings decrease owing to luminous flux degradation and building managers have the targeted energy savings they want to achieve over the evaluation period. The energy savings constraint is given as

$$ES_i(j) \geq \Phi, \tag{3.18}$$

where Φ is the targeted energy savings (in kWh). Φ is the percentage of energy consumption before the installation of the lighting control system.

(iii.) *Maintenance cost limit*

The maintenance cost at each sampling interval is set to be less than the cumulative energy saving costs.

$$\left(\sum_{k=1}^{j} ES_i(k) \times ET\right) - (U_p + L_c) \times m_i(j) \geq 0, \tag{3.19}$$

where ET is the electricity tariff (in R/kWh). ET is considered constant at each sampling interval.

3.4.4 Solution methodology

The optimization problem (3.6) - (3.19) is formulated as a mixed-integer programming (MIP), and is solved using the Constraint Integer Program (SCIP). SCIP is available in OPTimization Interface (OPTI) Toolbox[2] in MATLAB. SCIP is reported to be the fastest non-commercial MIP solver. The solver offers a solution to problems of the form:

$$\min \ f(X) \ ,$$

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

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

The performance of the solver is given by the case study discussed in the following section.

3.5 CASE STUDY

A lighting system in an open-plan office of a length of 15 m, a width of 10 m, and a height of 2.8 m (shown in Figure 3.1) is used as a case study. The office is equipped with an LED light system composed of 36 Philips LED tubes of 1200 mm, 20 W, 4000 K, and 2650 lm each. Each workstation is equipped with six LED tubes. A light sensor is installed in each workstation to adjust the lumen output to the light level required by users, and the occupancy sensor is installed to detect occupancy in each workstation. S1 and S4 are occupied 12 hours/day, S2 and S5 are occupied 10 hours/day, and S3 and S6 are occupied 7 hours/day. Users' light level is set at 300 in S1, S2, and S3, and at 500 lux in S4, S5, and S6.

3.6 SIMULATION RESULTS AND DISCUSSION

3.6.1 Results analysis

Simulation results are analysed under four scenarios: Scenario 1 presents the baseline; Scenario 2 presents the case where the maintenance is performed based on the IES LM-80-08 standard of LEDs failure; Scenario 3 presents a full maintenance plan, and Scenario 4 presents the optimal maintenance plan. All scenarios are simulated using MATLAB R2016b.

The data used in the simulations to validate the formulated models are presented in Table 3.1. The LED lights parameters (k_b, k_h and R_{th}) are obtained from the Philips manufacturing data sheet, the LED lighting system design parameters (U_f and M_f) are obtained from the reference [115], 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 the integrating sphere in the laboratory, 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 3.1. 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	$^{\circ}C/W$	$t_{s,3} = t_{s,6}$	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

3.6.2 Scenario 1

In the baseline scenario, the lighting system in the case study is analysed without lighting control system and maintenance. LED lights operate at their full brightness in all workstations. Illumination levels in all workstations and lighting energy consumption are calculated at each sampling interval using (3.1) and (3.12), respectively. Results show that the illumination level degrades over time in all workstations. The illumination level in the workstations decreases from 570 lux in the first month of operation to 343 lux at the end of the evaluation period. Figure 3.2 shows the degradation of luminous flux and illuminance levels over time. 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.

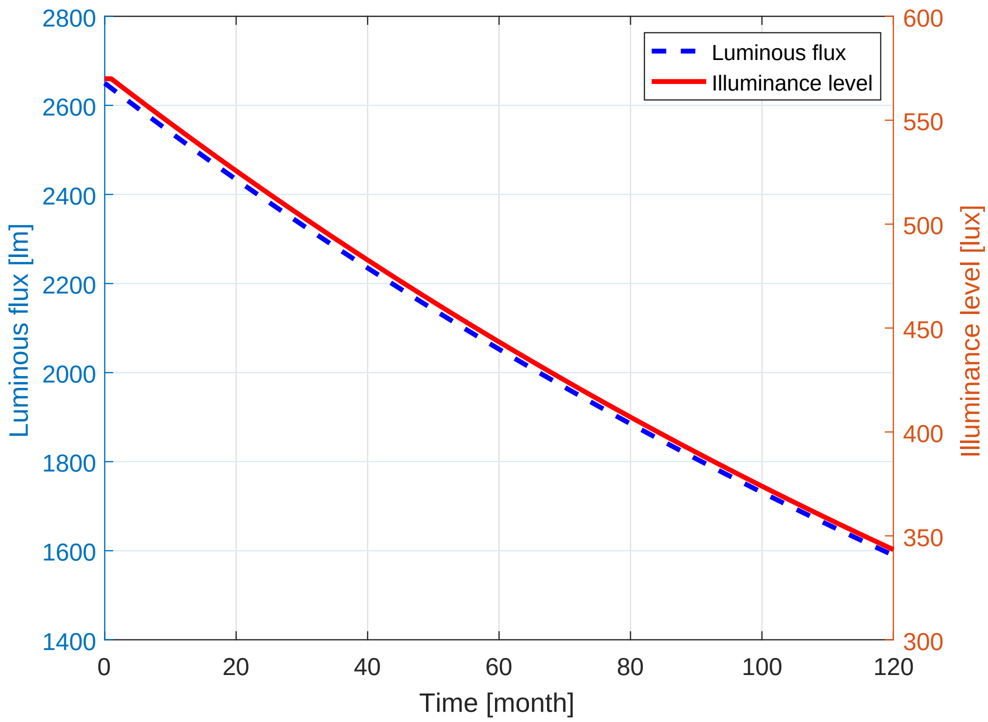

Figure 3.2. Luminous flux and illuminance degradation over time in Scenario 1.

3.6.3 Scenario 2

In this scenario, LED lights operate at their full brightness in all workstations and maintenance is performed based on the IES LM-80-08 standard. In the IES LM-80-08 standard, LEDs are declared to fail if the lumen output is less than 70% of the initial lumen output. Results show that lights in all workstations will be replaced after operating 84 months. Figure 3.3 shows the light level in workstations. It is noticed that illuminance decreases with time and increases when maintenance is performed. Energy consumption and maintenance costs over the evaluation period are 45.61 MWh and R 6 480, respectively.

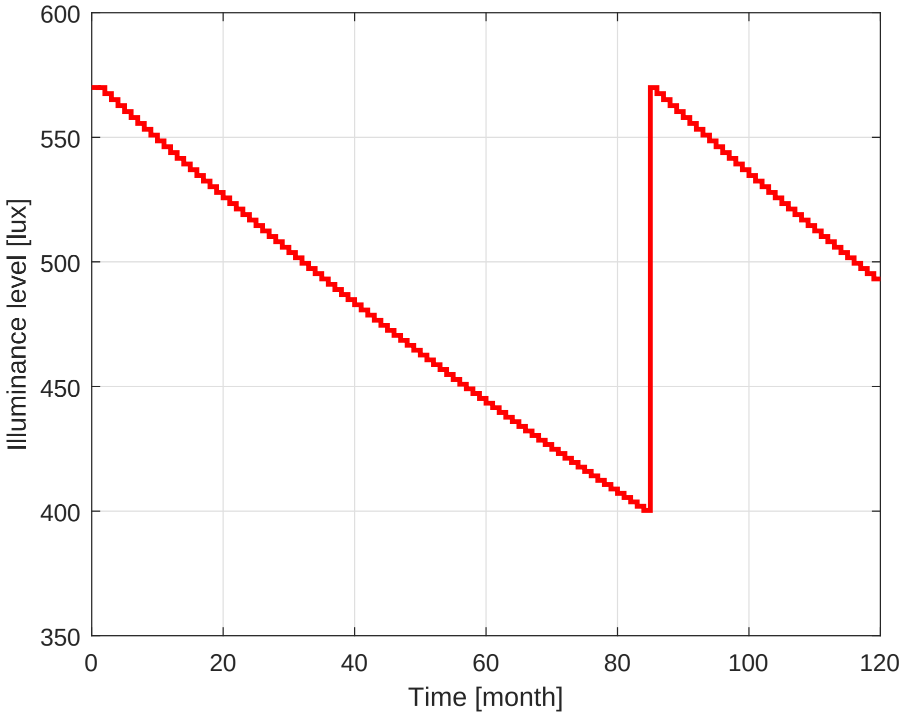

Figure 3.3. Illuminance level in workstations in Scenario 2.

3.6.4 Scenario 3

In this scenario, full maintenance is applied to maintain users' light level requirements. Full maintenance is referred to as the maintenance by which all lamps will be replaced by new ones once lamps in the workstation are not able to satisfy users' light level requirements. The light sensor installed in each workstation adjusts the lumen output to the light level required by users, and the occupancy sensor switches on when the workstation is occupied and off when is not occupied. Lamps in the workstation are dimmed when the measured light level is higher than the required level, and lamps are replaced when the measured light level is less than the required level. Results show that maintenance will not be performed in S1, S2, and S3, because lamps in these workstations satisfy users' light level requirements over the evaluation period. In S4, S5, and S6 lamps will be replaced every 44, 56, and 68 months, respectively. Figure 3.4 presents energy savings in each workstation over time. Energy savings over the evaluation period in S1, S2, S3, S4, S5, and S6 are 5.5 MWh, 5.97 MWh, 6.54 MWh, 4.13 MWh, 4.6 MWh, and 5.2 MWh, respectively. In this scenario, 31.94 MWh are saved. Failed lamps are replaced at a cost of R 5 400.

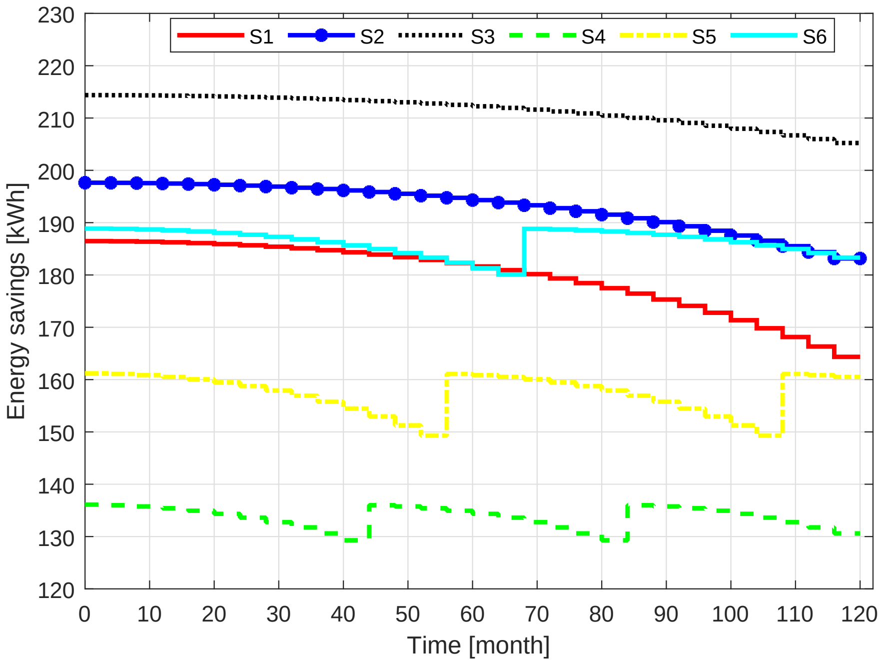

Figure 3.4. Energy savings in each workstation under Scenario 3.

3.6.5 Scenario 4

In this scenario, the proposed maintenance plan is applied to the lighting system in the case study. As discussed in Subsection 3.4.4, to obtain the optimal solution the optimization problem is solved using the SCIP solver. The objectives are treated as equal, thus the weighting coefficients are equal (i.e. $\omega_1 = \omega_2 = 0.5$). At each sampling interval, the solver determines the optimal dimming level and the number of lamps to be replaced in each workstation. The optimal number of lamps to be replaced and the dimming levels in each workstation are shown in Figures 3.5 and 3.6, respectively. Results show that the first replacement of three lamps occurs after 36 months in S4. The user-set illuminance level and lights' daily usage affect the optimal solution significantly. Workstations with high user-set illuminance levels and more operating hours are maintained more often than others. For example, S4, and S5 are maintained three times each, while maintenance is not carried out in S1, S2, and S3. The lights in S1, S2, and S3 are not maintained over the evaluation period; their luminous flux decreases but still meets the user-set illuminance level. From Figure 3.7, it is noted that the higher the number of replacements, the lower the dimming level. Results show that the optimal number of replacements and dimming levels can vary with the weighting coefficients. For example, for $w_1 = 0.5$, and $w_2 = 0.5$, 21 lights are replaced over the evaluation period, while for $w_1 = 0.7$, and $w_2 = 0.3$, 24 lights are replaced over the evaluation period. Results show that 31.27 MWh of the lighting energy consumption can be saved in this scenario at a maintenance cost of R 3 780. Table 3.2 presents and compares the project key performance factors under the scenarios analysed.

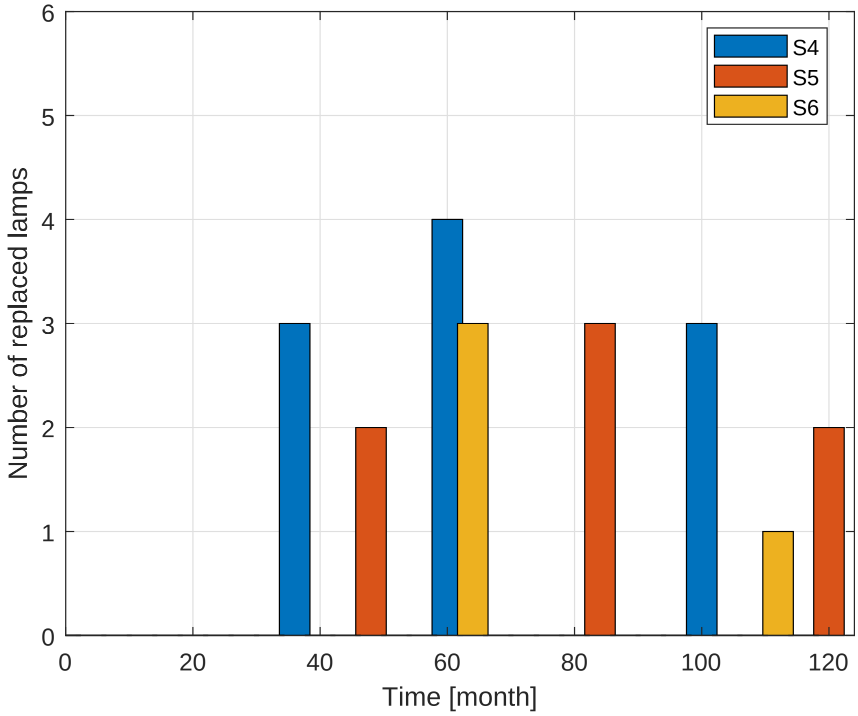

Figure 3.5. Optimal number of lamps replaced under Scenario 4.

Table 3.2. 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	**R 43 338**	**R 49 818**	**R 18 387**	**R 17 403**

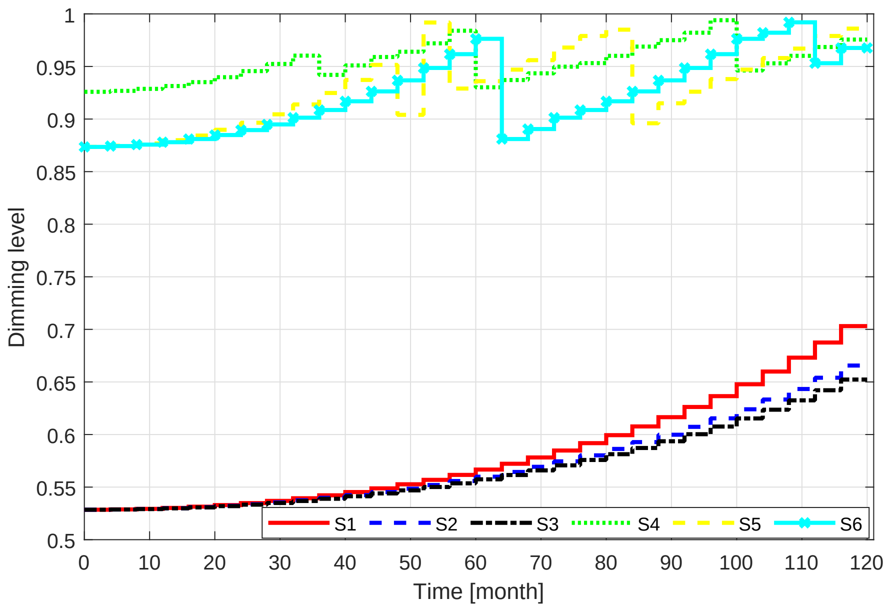

Figure 3.6. Dimming level in each workstation under Scenario 4.

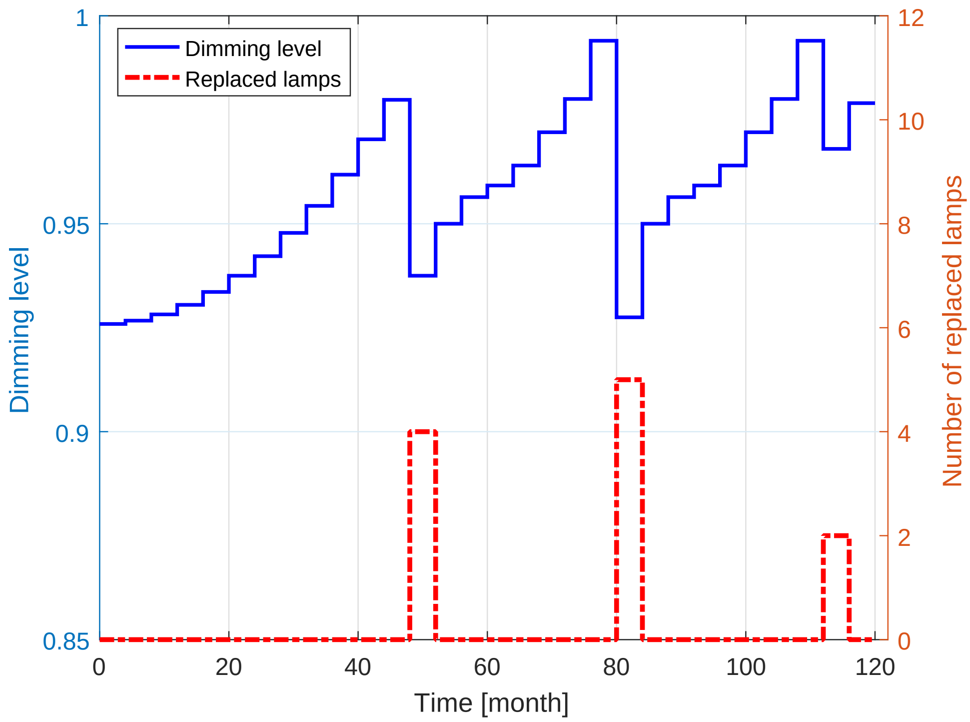

Figure 3.7. Dimming level and number of lamps replaced in Z4 under Scenario 4.

3.7 CHAPTER SUMMARY

In this chapter, an energy-maintenance optimization model is formulated to minimize lighting energy use and maximize maintenance cost, while satisfying users' illumination level requirements. The results of the case study demonstrated the effectiveness of the proposed energy-maintenance optimization model. From the case study results, it is concluded that to save more energy, lighting controls should be included in EE lighting retrofit projects; maintenance should be planned to maintain users' lighting level requirements, and optimal maintenance is the most cost-effective maintenance compared to full maintenance and lumen threshold-based maintenance.

CHAPTER 4 OPTIMAL MAINTENANCE PLAN INCORPORATING LUMEN DEGRADATION FAILURE FOR LIGHTING RETROFITTING PROJECTS

4.1 CHAPTER OVERVIEW

This chapter continues in the line of Chapter 3 by considering large-scale lighting retrofit projects. In large-scale lighting retrofit projects, monitoring when each lamp will fail can be time-consuming and costly. In this work, the degradation failure model is developed by analysing the statistical properties of sample lumen degradation rates. This model considers the variations in lumen degradation rates which may be caused by manufacturing materials and processes, or different handling conditions. By using the Kaplan-Meier method, the formulated lumen degradation failure is used to model the surviving population. Thereafter the surviving population model is used to design an optimal lighting maintenance plan, which maximizes energy savings and minimizes maintenance costs. The effectiveness of the formulated maintenance plan is demonstrated by an actual residential LED lighting retrofit project implemented in South Africa. The work done in this chapter is published in [116].

4.2 INTRODUCTION

Generally, lighting retrofit projects contain a large lighting population. Over time, the lighting population decreases owing to either burnout failure or lumen degradation failure. These failures lead to a reduction in the illumination level and energy savings if proper maintenance is not performed. For EE lighting retrofit projects registered under incentive programs such as Clean Development Mechanism (CDM), to maintain the performance of the implemented project, a penalty factor to the energy savings is introduced. This entails that for the project to earn the annual energy savings rebate, the surviving population should be greater than 50% of the initial population. In consideration of lumen degradation, the ASSIST recommends a 70% lumen (30% degradation from the initial lumen output) threshold to determine the useful life of LEDs for general lighting applications. Therefore, for LED-based lighting retrofit projects, a 70% lumen degradation criterion should be considered to maintain both the illumination level and energy savings, since the burnout failure is not significant, in view of the longevity of LEDs.

The main contribution of this chapter is the formulation of optimal lighting maintenance that takes into account lumen degradation failure based on the statistical properties of the lumen degradation rates.

4.3 PROBLEM FORMULATION AND MODELLING

The project developers implemented an LED-based lighting retrofit project and registered the project under an incentive program to earn an energy saving rebate. For this project to earn an annual rebate, the surviving population had to be greater than 70% of the initial population. At the installation stage, all the installed lamps operate properly, but as time goes by the number of lamps working properly reduces owing to lumen degradation failure. To maintain the project performance and earn an energy saving rebate, maintenance is needed. However, maintenance activities are very costly and time-consuming when a large lamp population is involved. This chapter, therefore, aims to propose an optimal lighting maintenance plan that maximizes energy savings and minimizes maintenance costs, while taking into account the lumen degradation failure.

For the formulation of the lighting maintenance optimization problem, lamp lumen degradation failure is modelled.

4.3.1 Lumen degradation failure modelling

LED lamp failure based on lumen degradation is modelled to predict the surviving population in LED-based lighting retrofit projects. The lumen degradation of LEDs is calculated using exponential decay model as

$$\phi(t) = \phi(0)e^{-\beta t}, \tag{4.1}$$

where $\phi(t)$ is the luminous flux (in lm) at time t, $\phi(0)$ is the initial luminous flux (in lm), and β is the degradation rate.

The failure rate may vary among LEDs owing to variations in lumen degradation, and the lumen degradation rate may vary among LEDs because of variations in materials, different manufacturing processes, or different handling conditions. For this reason, in this study LEDs' failure is modelled by analysing the statistical properties of the lumen degradation rates. The modelling process is detailed as follows:

i) *Lumen measurement*

Currently, there is no universal standard for measuring the photo-metric properties of LEDs. The Illumination Engineers Society (IES) released documents (IES LM-80-08 and IES LM-IES TM-21-11) describing standards for testing LEDs [117]. These standards appear to be the front-runners in becoming the benchmark standards in testing photo-metric properties and have been adopted by most top-tier manufacturers such as Osram and Philips. Because of their longevity, up to now, there have been no actual measurement data of lumen degradation of LEDs over their complete lifetime. In this study, the data used to model lumen degradation failure have been obtained from the Illuminating Engineering Society of North America (IESNA) LM-80 test report of Philips Lumileds [57]. In this report, lumen degradation of 25 LUXEON Rebel, Lumileds Philips lamps are tested in compliance with the LM-80-08 standard. Luminous flux data of tested units are collected every 1 000 hours over an evaluation period of 7 000 hours. All collected luminous flux data are normalized to 1 at the original test point. Sample test units are tested in homogeneous operating and environmental conditions. A lumen degradation threshold (Lp_{th}) of 70% (commonly used in general lighting applications) is considered. When the lumen degradation of a unit at any time t is below Lp_{th}, the unit is deemed as failed.

ii) *Estimation of degradation rates and statistical property analysis*

The degradation rate of each test unit is estimated using regression analysis. Regression analysis examines the relationship between time and lumen degradation. Each test unit is represented by time and lumen degradation data points, $(t_1, Lp_1), \cdots, (t_K, Lp_K)$. The model function of each unit is given as

$$Lp_i = f(t, \beta_i),\ i = 1, 2, \cdots, n,\ t = 1, 2, \cdots, K, \tag{4.2}$$

where Lp_i and β_i are the lumen measurement and degradation rate of the ith unit, respectively. It is found that the test units data are characterized by exponential models with the coefficient of determination (R^2) between 0.97 and 0.99. The estimated degradation rates for each unit are given in Table 4.1.

To analyse the statistical properties of the degradation rates, the probability distribution fitting is used to determine the statistical distribution that best fits the degradation rates. There are different distribution fitting programs, including EasyFit, Matlab, Excel, ExpertFit, and R. In this study, EasyFit[1] is used. Kolmogorov Smirnov, Anderson Darling, and Chi-Squared tests are used to test the best fit. Table 4.2 presents different tested distributions and their statistics. The distribution fits are tested at a 95% confidence level. Results show that the degradation rates fit 40 distributions out of 57 fitted distributions. It is found that the Generalized Extreme Value (GEV) distribution is the best fit, and this is used to estimate the cumulative probability of failure distribution.

iii) *Model prediction*

The probability that a brand new LED will fail at or before a specified time is represented by a cumulative distribution function $F(t)$. $F(t)$ is expressed as [118]

$$F(t) = P[\varepsilon \leq t], \tag{4.3}$$

where ε is the lifetime of LED (hours of use before LED fails). Assuming β of the LED is known and Lp_{th} is set, ε can be expressed as [119]

$$\varepsilon = \frac{\ln\left[Lp_{th}\right]}{-\beta}. \tag{4.4}$$

Substituting (4.4) in (4.3) one obtains

$$F(t) = P\left[\frac{\ln\left(Lp_{th}\right)}{-\beta} \leq t\right]. \tag{4.5}$$

[1] http://www.mathwave.com/easyfit-distribution-fitting.html

Table 4.1. Lumen degradation rates of test units over the evaluation period of 7 000 h.

Test unit	β	Test unit	β
1	0.1382×10^{-4}	14	0.0908×10^{-4}
2	0.1211×10^{-4}	15	0.1609×10^{-4}
3	0.1346×10^{-4}	16	0.1008×10^{-4}
4	0.1274×10^{-4}	17	0.1097×10^{-4}
5	0.1001×10^{-4}	18	0.1287×10^{-4}
6	0.1177×10^{-4}	19	0.1462×10^{-4}
7	0.1192×10^{-4}	20	0.0902×10^{-4}
8	0.1142×10^{-4}	21	0.1312×10^{-4}
9	0.1368×10^{-4}	22	0.1015×10^{-4}
10	0.1142×10^{-4}	23	0.1508×10^{-4}
11	0.1428×10^{-4}	24	0.1053×10^{-4}
12	0.1269×10^{-4}	25	0.1206×10^{-4}
13	0.1386×10^{-4}		

β_i follows the GEV distribution with shape parameter ι, location parameter ν, and scale parameter κ. $\beta \sim$ GEV (ι, ν, κ), the GEV cumulative distribution is given as [120]

$$F(t) = P\left[\frac{\ln\left(Lp_{th}\right)}{-\beta} \leq t\right] = exp\left[-\left(1-\left(\frac{\frac{\ln\left(Lp_{th}\right)}{-t}-\iota}{\nu}\right)\times\kappa\right)^{\frac{1}{\kappa}}\right]. \tag{4.6}$$

After modelling the failed proportions $F(t)$, the surviving population is estimated using the Kaplan-Meier method [121] as

$$N(t+1) = N(t)\prod_{j=1}^{t}\left(1-\frac{d(j)}{N(j)}\right), \tag{4.7}$$

where $d(j) = N(j-1)F(j)$ is the number of LEDs failed at time j (with luminous flux below the threshold).

iv) *Model parameter estimation*

Parameter estimation methods including the mixed-method [122], maximum likelihood method [120], and probability weighted moment (PWM) method [123] have been used to estimate GEV distribution parameters. Reference [123] shows that maximum-likehood estimators are unstable for a small sample and recommends the PWM estimators. The PWM estimators are equivalent to L-moment estimators [124]. By using the L-moment estimators, the GEV distribution parameters are given as [124]

$$\hat{\iota} = \hat{\lambda}_1 - \frac{\hat{\nu}}{\hat{\kappa}}\bigg(1 - \Gamma(1+\hat{\kappa})\bigg), \tag{4.8}$$

$$\hat{\nu} = \frac{\hat{\lambda}_2 \hat{\kappa}}{(1-2^{-\hat{\kappa}})\Gamma(1+\hat{\kappa})}, \tag{4.9}$$

$$\hat{\kappa} = 7.8590c + 2.9554c^2, \;\; c = \frac{2}{3+\hat{\tau}} - \left(\frac{\ln 2}{\ln 3}\right), \tag{4.10}$$

where $\hat{\tau} = \hat{\lambda}_3/\hat{\lambda}_2$, and $\Gamma(\cdot)$ is the complete gamma function. Parameters $\hat{\lambda}_1, \hat{\lambda}_2,$and $\hat{\lambda}_3$ are given as [125]

$$\hat{\lambda}_1 = b_0, \tag{4.11}$$

$$\hat{\lambda}_2 = 2b_1 - b_0, \tag{4.12}$$

$$\hat{\lambda}_3 = 6b_2 - 6b_1 + b_0, \tag{4.13}$$

and b_0, b_1, b_2 are unbiased estimators calculated using (4.14) [126]

$$b_r = \frac{1}{n}\sum_{j=1}^{n}\left[\frac{(j-1)(j-2)\cdots(j-r)}{(n-1)(n-2)\cdots(n-r)} Lp_{n-j+1:n}\right], \;\; r = 0,1,2. \tag{4.14}$$

In practice, the parameters ι, ν, and κ may not be known accurately beforehand. Based on lumen degradation data available at each time t, the failed proportions can be expressed as

$$F(t) = f(t, \iota_t, \nu_t, \kappa_t), \tag{4.15}$$

where ι_t, ν_t, and κ_t can be determined at each time interval using (4.14).

v) *Applicability of the model*

The models (4.6) and (4.7) are applicable to LUXEON rebel LEDs operating under normal indoor conditions. In this study, these models are used to develop an optimal maintenance plan of the LUXEON-based LED lighting retrofit project in residential buildings.

Table 4.2. Tested distributions using goodness fit tests.

N0	Distribution	Kolmogorov Smirnov Statistic	Kolmogorov Smirnov Rank	Anderson Darling Statistic	Anderson Darling Rank	Chi-Squared Statistic	Chi-Squared Rank
1	Beta	0,13345	37	4,2804	42	N/A	-
2	Burr	0,07417	6	0,14771	6	0,40447	10
3	Burr (4P)	0,72372	53	15,225	52	0,08885	5
4	Cauchy			Reject			
5	Dagum	0,0989	27	0,27946	27	0,91312	16
6	Dagum (4P)			Reject			
7	Erlang	0,10107	28	0,21429	19	1,1869	33
8	Erlang (4P)	0,10167	29	0,21717	20	1,2339	34
9	Error	0,065	3	0,11954	3	0,05274	4
10	Error function			Reject			
11	Exponential			Reject			
12	Exponential (2P)			Reject			
13	Fatigue life	0,09586	25	0,22367	21	1,1334	29
14	Fatigue life (3P)	0,07848	11	0,15991	9	0,38145	9
15	Frechet	0,15555	41	0,80594	35	1,9925	37
16	Frechet (3P)	0,11238	31	0,37649	30	0,86061	13
17	Gamma	0,0868	16	0,1815	14	1,0919	21
18	Gamma (3P)	0,08357	15	0,17538	11	1,1005	22
19	Gen. Extreme Value	0,06181	1	0,11934	2	0,02251	1
20	Gen. Gamma	0,08757	18	0,19079	16	1,1054	24
21	Gen. Gamma (4P)	0,17954	42	4,7381	45	N/A	-
22	Gen. Logistic	0,07572	8	0,17576	12	0,89488	15
23	Gen. Pareto	0,09732	26		Reject		
24	Gumbel Max	0,13582	38	0,69617	34	1,1247	27
25	Gumbel Min	0,12555	35	0,50988	31	1,1048	23
26	Hypersecant	0,09581	24	0,33599	28	2,0534	38
27	Inv. Gaussian	0,09461	21	0,24275	25	1,1103	25

		Kolmogorov Smirnov		Anderson Darling		Chi-Squared	
N0	Distribution	Statistic	Rank	Statistic	Rank	Statistic	Rank
28	Inv. Gaussian (3P)	0,13287	36	1,0899	36	1,4291	35
29	Johnson SB	0,06181	1	0,11954	3	0,04739	3
30	Kumaraswamy	0,14292	39	4,365	44	N/A	-
31	Laplace	0,11644	32	0,54984	32	1,8644	36
32	Levy			Reject			
33	Levy (2P)			Reject			
34	Log-Logistic	0,12391	34	0,34163	29	0,86605	14
35	Log-Logistic (3P)	0,07821	10	0,18234	15	0,91584	17
36	Log-Pearson 3	0,07743	9	0,15157	7	0,34299	7
37	Logistic	0,08736	17	0,23458	24	1,0031	19
38	Lognormal	0,09577	23	0,22402	22	1,1293	28
39	Lognormal (3P)	0,08127	14	0,17376	10	1,1136	26
40	Nakagami	0,07875	12	0,15949	8	0,36317	8
41	Normal	0,07244	5	0,13822	5	0,03183	2
42	Pareto			Reject			
43	Pareto 2			Reject			
44	Pearson 5	0,10372	30	0,26755	26	1,0735	20
45	Pearson 5 (3P)	0,09124	19	0,19634	17	1,1607	32
46	Pearson 6	0,09168	20	0,20607	18	1,1498	30
47	Pearson 6 (4P)			Reject			
48	Pert			Reject			
49	Power function	0,118	33	Reject		1	18
50	Rayleigh			Reject			
51	Rayleigh (2P)	0,15047	40	0,64834	33	0,57672	12
52	Reciprocal			Reject			
53	Rice			Reject			
54	Uniform			Reject			
55	Wakeby	0,06932	4	0,11185	1	0,13297	6
56	Weibull	0,07419	7	0,23448	23	0,54344	11
57	Weibull (3P)	0,08051	13	0,1758	13	1,1583	31

4.4 OPTIMIZATION FORMULATION

The maintenance plan considering lumen degradation failure is developed into an optimization problem. The number of replacements is optimized to maximize energy savings and minimize maintenance cost. The optimization problem is formulated in the subsections below.

4.4.1 Design variables

Let $u(j)$ denote the number of failed lamps to be replaced at time j. The design variable of the maintenance problem within the evaluation period J is given as

$$X = \Big[u(1), u(2), \cdots, u(J)\Big]^T. \tag{4.16}$$

The design variables are integers bound between 0 and the initial lighting population.

$$L_b = [0, \cdots, 0]^T_{J\times 1}, \quad U_b = [N(0), \cdots, N(0)]^T_{J\times 1}, \tag{4.17}$$

where L_b and U_b are the lower and upper bounds of the design variables.

4.4.2 Objective

The objective of designing an optimal lighting maintenance plan is to maximize energy savings and minimize maintenance cost.

$$\begin{cases} \min & -\Theta \\ \min & M_c \end{cases} \tag{4.18}$$

where Θ and M_c are the energy savings (in kWh) and maintenance cost (in R) over the evaluation period, respectively. The weighted sum method [114] is used to integrate objective functions (4.18) into one objective function. This approach gives the project developers advantage of determining the weights in order to achieve their desired performance.

$$\min \quad W = -\alpha_1 \Theta + \alpha_2 M_c \ , \tag{4.19}$$

where $\alpha_1$and α_2 are the weighting coefficients, which are in range $[0, 1]$, and $\alpha_1 + \alpha_2 = 1$. To normalize the objective function (4.19), the maximum values of energy savings ($\overline{\Theta}$) and maintenance cost ($\overline{M}_c$)

are used, and the objective function (4.19) is re-written as

$$\min \quad W = -\alpha_1 \frac{\Theta}{\overline{\Theta}} + \alpha_2 \frac{M_c}{\overline{M_c}}. \tag{4.20}$$

Θ is expressed as the product of energy saving per retrofitted lamps and the number of surviving lamps.

$$\Theta = \sum_{j=1}^{J} ES \times N(j) \ , \tag{4.21}$$

where ES is the energy savings (in kWh) per retrofit unit. The ES is determined using an M&V approach [127].

By considering maintenance, the surviving population is expressed as

$$N(j+1) = N(j) \prod_{t=1}^{j} \left(1 - \frac{d(t)}{N(t)}\right) + u(j), \tag{4.22}$$

Time $j = 0$, is regarded as the installation stage, and the surviving population at $j = 0$ is equal to the initial installed lighting population $N(0)$. The failed lamps will be replaced by the same type of lamps, which will not change the population degradation distribution. The maintenance cost of replacing the failed lamps by new ones is given as

$$M_c = \sum_{j=1}^{J} \left(\sigma_0 + L_c\right) \times u(j), \tag{4.23}$$

where σ_0 is the price (in R) of each bulb , and L_c is the labour cost (in R) to replace a bulb. The labour cost is calculated as minutes to change a bulb (average of eight minutes is used) divided by 60 minutes in an hour times hourly rate for lighting maintenance (this value is obtained from South African labour costs data 2008 - 2016). The hourly rate for lighting maintenance used is for indoor lighting applications. Thus, the unit labour cost considered is for indoor lighting applications.

4.4.3 Constraint

In order to earn the annual savings rebate the number of surviving lamps should be greater than or equal to 70% of the initial population.

$$N(j) \geq 0.7 \times N(0) \ , \tag{4.24}$$

and $N(j)$ should not be higher than the initial population

$$N(t) \leq N(0) \ . \tag{4.25}$$

The maintenance budget limit constraint (4.26) indicates that the maintenance cost over the evaluation period should not exceed the initial investment ζ.

$$\sum_{j=1}^{J} \big(\sigma_0 + L_c\big) \times u(j) \leq \zeta \ . \tag{4.26}$$

ζ is expressed as

$$\zeta = \big(\sigma_0 + L_c\big) \times N(0). \tag{4.27}$$

4.4.4 Solution methodology

The lighting optimization problem is formulated as an integer programming problem, and is solved using the Mixed Integer Distributed Ant Colony Optimization (MIDACO) solver, which is a numerical high-performance solver for single and multi-objective optimization problems. The MIDACO solver can be applied to continuous, discrete/integer, and mixed-integer problems. It is available for several programming languages including MATLAB, Octave, and Python [128]. In this study, it is used in MATLAB R2017b.

MIDACO offers solutions to problems of the form [128]:

$$\begin{aligned} &\text{minimize} \;\; f(x,y) \ , \\ &\text{subject to:} \begin{cases} g_h(x,y) = 0, \;\; h = 1,\cdots,m_e \in \mathbb{N}, \\ g_h(x,y) \geq 0, \;\; h = m_e+1,\cdots,m \in \mathbb{N}, \\ x_l \leq x \leq x_u, \\ y_l \leq y \leq y_u, \end{cases} \end{aligned} \tag{4.28}$$

where $f(x,y)$ is the objective function to be minimized and $g_h(x,y)$ represents the vector of equality and inequality constraints. x and y are the continuous and discrete decision variables, respectively. x_l and y_l represent the lower bounds, and x_u and y_u represent the upper bounds of the decision variables x and y.

4.5 CASE STUDY

The formulated model is used to plan effective strategic maintenance for lighting retrofit projects. In South Africa, Eskom[2] in its program of residential mass roll-out (RMR) encourages project developers

[2] A South African electricity public utility

to implement EE lighting retrofit projects [129]. In one of the sub-RMR projects, LED light bulbs are replacing halogen light bulbs in households in different provinces of South Africa. LEDs that are installed have the equivalent lumen output to the replaced halogen. LUXEON-based LED light bulbs with a rated power of 10 W and lumen output of 800 lm are considered to replace halogen light bulbs of the rated power of 50 W and lumen output of 800 lm. The lighting retrofit project is evaluated for a duration of K = 10 years, with a sampling interval of 1 year. The case study key information is given in Table 4.3.

The EE lighting retrofit projects contain a large lighting population, thus installing a light meter to each light bulb is not feasible because of the high cost of light meters. The simple random sampling approach is used to determine the required sample lights for a given population to achieve some confidence and precision. The sample size (n) for the lighting population is calculated as [130]

$$n = \frac{z^2 CV^2}{p^2}, \tag{4.29}$$

where z is the z-score, p is the relative precision, and a CV is the standard deviation of the sampling records divided by the mean.

The CDM guidelines of 90% of the confidence interval and 10% of relative precision, and the CV of 0.5 are applied in the calculation. To ensure accurate and representative luminous flux data, the following protocols are applied to measure the luminous flux: i) only the light provided by the lamp being tested is measured; ii) luminous flux measurements are recorded at a typical office desk height (0.76 m); iii) the same type of calibrated lux meters are used; iv) adjacent electric lights are switched off during measurement, and v) measurements are scheduled and taken every day after sunset to avoid daylight disturbance. The luminous flux collected at each sampling interval is normalized to the initial luminous flux.

Table 4.3. Case study information.

Parameter	Existing lights (halogen)	LED light bulb
Power	50 W	10 W
Light output	800 lm	800 lm
Lifetime	1 500 h	15 000 - 40 000 h
Operating hours/day	10 h	10 h
Initial population	207 693	207 693
Unit price	R 35	R 50
Replacement cost/bulb	-	R 7

4.6 SIMULATION RESULTS AND DISCUSSION

To assess the effectiveness of the maintenance plan developed, the no maintenance and full maintenance scenarios are simulated for comparison purposes.

4.6.1 No maintenance scenario

In the no maintenance scenario, the lighting project in Section 4.5 is implemented without maintenance. The number of failed and surviving lamps is estimated at each sampling interval using (4.6) and (4.7), respectively. As shown in Figure 4.1, the number of surviving lamps decreases over time and reaches the minimum number (70% of N(0)) required for an adequate illumination level after operating for 21 860 hours. The total energy savings over 10 years are 177.9×10^3 MWh.

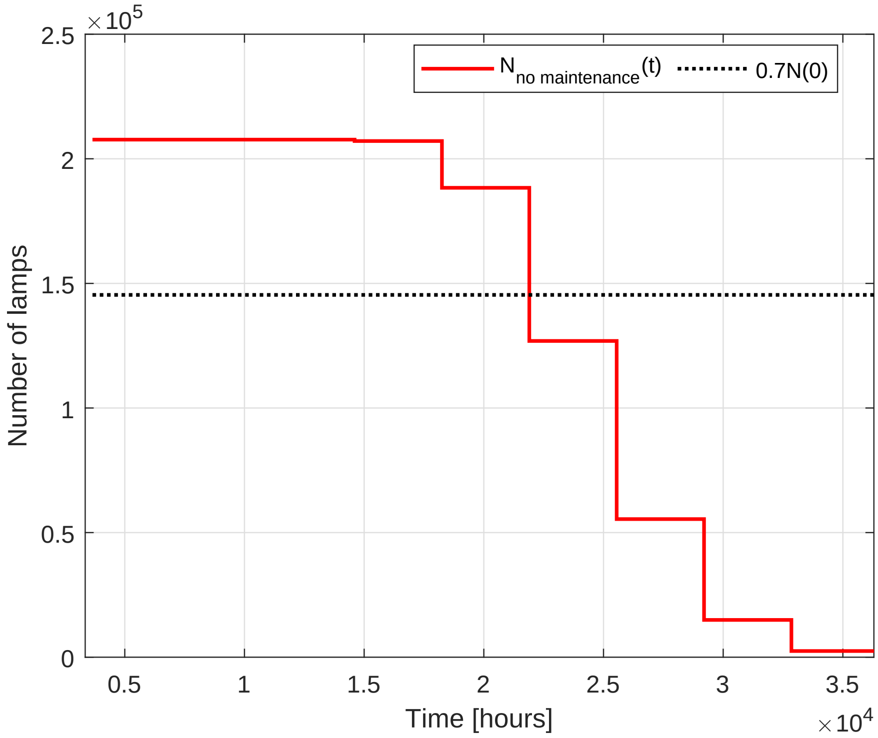

Figure 4.1. Surviving lamp population under no maintenance and threshold surviving lamps.

4.6.2 Full maintenance scenario

Full maintenance refers to maintenance under which all lamps will be replaced by new ones once the number of surviving lamps has reached 70% of N(0). All lamps will be replaced after every 21 860 hours of operation. Full maintenance will be performed once over the evaluation period. The total energy savings under full maintenance are 297.6×10^3 MWh, and the cost of full maintenance is R11 838 501.

4.6.3 Optimal maintenance scenario

In this scenario, the proposed maintenance plan is applied to the lighting retrofit project in the case study. The optimization problem is solved using the MIDACO solver. The parameters used in the solver are given in Table 4.4. The objectives are treated as equal, thus the weighting coefficients are equal (i.e. $\omega_1 = \omega_2 = 0.5$). At each sampling interval, the luminous flux collected is normalized to the initial luminous flux and used to calculate (4.14), then distribution parameters and the number of failed lamps are calculated. The energy savings and surviving population are calculated using (4.21) and (4.22), respectively. Results show that the first replacement of 7 996 lamps will happen at 18 250 hours, and 143 456 failed lamps will be replaced over the evaluation period. The optimal number of lamps to be replaced and the surviving population at each sampling interval are shown in Figure 4.2. The total energy savings under the optimal maintenance plan are 282.2×10^3 MWh, and the maintenance cost is R 8 176 992.

Compared to the no maintenance scenario, the optimal maintenance plan increases energy savings by 59%. A full maintenance plan produces more energy savings than the optimal maintenance plan because more failed lamps are replaced, but at higher maintenance cost. Figure 4.3 compares energy savings under the no maintenance, full maintenance, and optimal maintenance scenarios. Both the full maintenance and optimal maintenance plans maintain lumen degradation within the threshold. Table 4.5 presents and compares the project key performance factors under the full maintenance and optimal maintenance plans. It is observed that the optimal maintenance plan is more cost-effective (with R 78.3 per MWh saved) than a full maintenance plan. The ratio between the maintenance cost and additional energy savings is calculated to indicate the cost-effectiveness of different maintenance plans.

Table 4.4. Solver parameters.

Parameter name	Value
problem.o (number of objectives)	1
problem.n (number of variables)	10
problem.ni (number of integer variables)	10
problem.m (number of constraints in total)	21
problem.me (number of equality constraints)	0
problem.xl (lower bound)	0×ones(1,problem.n)
problem.xu (upper bound)	N(0)×ones(1,problem.n)

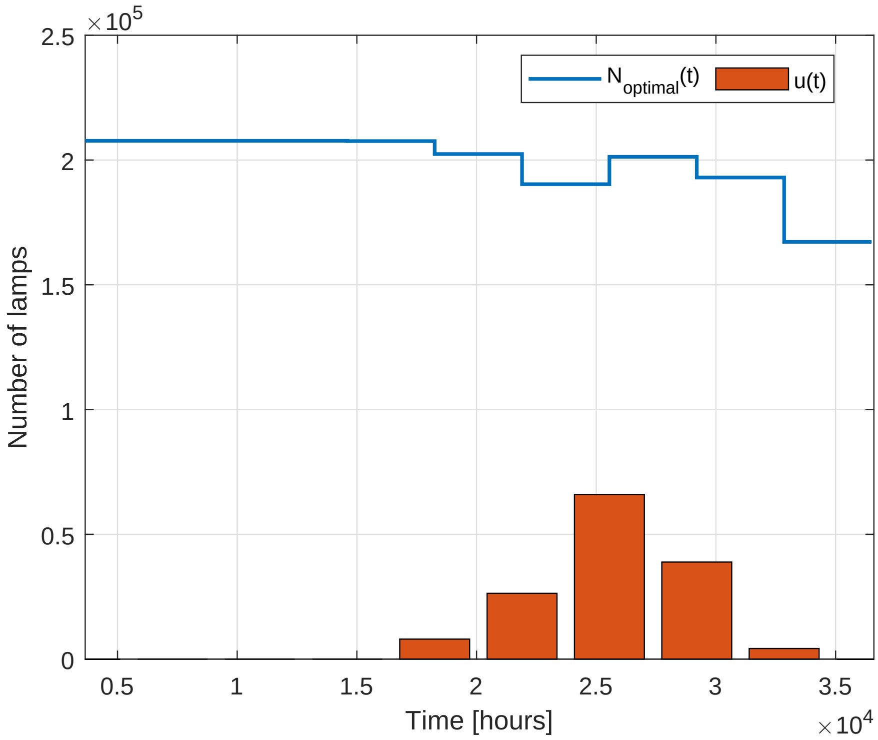

Figure 4.2. Optimal number of lamps to be replaced and surviving population.

Table 4.5. Project key performance factor analysis under full and optimal maintenance.

Factor	Full maintenance (FM)	Optimal maintenance (OM)
Energy savings (MWh)	297.6×10^3	282.2×10^3
Number of replaced lamps	207 693	143 456
Maintenance cost (R)	11 838 501	8 176 992
Performance indicator (R/MWh)	**98.9**	**78.3**

4.6.4 Sensitivity analysis

Uncertainties associated with parameters used in the optimization are discussed as follows:

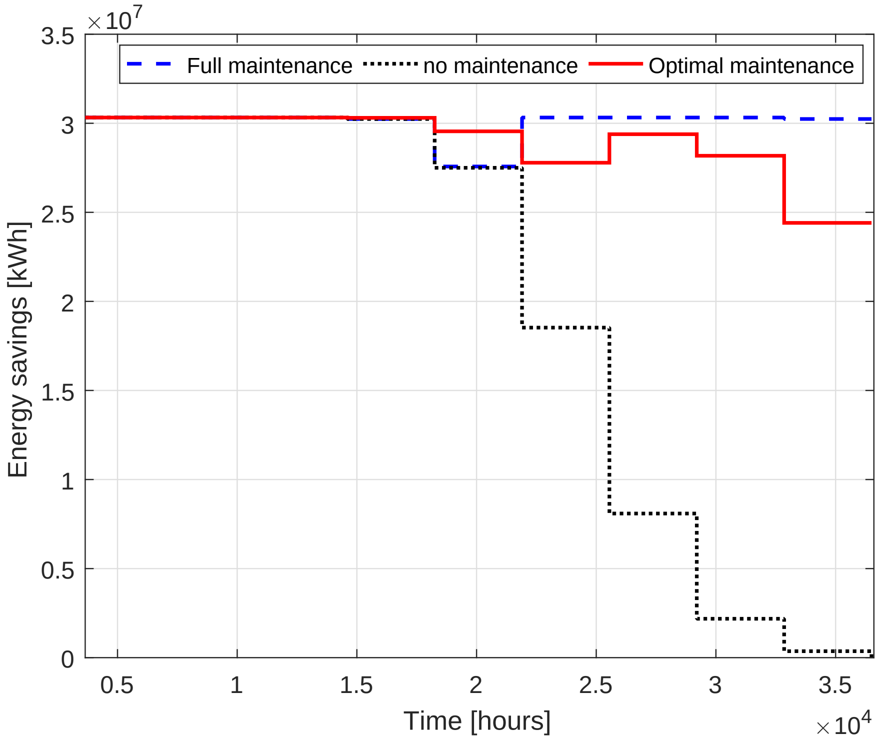

Figure 4.3. Energy savings under no maintenance, full maintenance, and optimal maintenance scenarios.

i) *Weighting coefficients*

The weighting coefficients are selected depending on the project developers' preferences. The higher the weighting coefficient, the more preference is given to the associated objective. Results show that the optimal number of lamps to be replaced varies with the weighting coefficients. For example, for $\omega_1 = \omega_2 = 0.5$, 143 456 failed lamps will be replaced, while for $\omega_1 = 1$, and $\omega_2 = 0$, 166 154 failed lamps will be replaced.

ii) *Daily light usage*

In the case study, the daily light usage of 10 hours is considered, but the daily usage may increase or decrease depending on users' behaviour and occupancy patterns. Simulation results show that the optimal number of lamps to be replaced is sensitive to the number of operating hours. When the operating hours increase, the number of lamps to be replaced increases, and when the operating hours decrease, the number of replacements decreases.

iii) *Light price*

The price of LED lights has dropped significantly over the past few years and the trend is expected to continue owing to the rapid development of LED technology. Results show that the optimal number of lamps to be replaced is sensitive to the unit price of LED. When the unit price of LEDs decreases, the number of lamps to be replaced increases.

iv) *Lighting population size*

In lighting retrofit projects, the initial population size differs from one project to another. Results show that the optimal number of lamps to be replaced increases when the initial population increases and decreases when the initial population decreases. For example, if the initial population is increased by 25%, the number of lamps to be replaced increases to 173 302. Table 4.6 presents the sensitivity of the optimization parameters.

Table 4.6. Sensitivity analysis of the optimization parameters.

	Weighting coefficients		Light daily usage		Light price		Initial population	
Factor	$\omega_1 = \omega_2 = 0.5$	$\omega_1 = 1, \omega_2 = 0$	10 h	4 h	R 50	R 40	207,693	259,617
Energy savings (GWh)	282.2	287.4	282.2	286.3	282.2	283.7	282.2	191.6
Number of replaced lamps	143 456	166 154	143 456	0	143 456	145 231	143 456	173 302
Maintenance cost (R)	8 176 992	9 470 778	8 176 992	0	8 176 992	6 825 857	8 176 992	9 878 214

4.7 CHAPTER SUMMARY

This chapter is based on our published work [116]. An optimal maintenance plan for an LED lighting retrofit project is studied in this chapter. A lumen degradation failure model is developed for LUXEON-based LED lights. Based on the statistical properties of the degradation rates, the cumulative probability of failure distribution and the survival function are modelled. The formulated survival function is incorporated into the lighting maintenance optimization problem to balance energy savings and maintenance costs. A case study carried out shows that, in 10 years, the optimal lighting maintenance plan would save up to 59% of lighting energy consumption with acceptable maintenance costs. It is found that the proposed maintenance plan is more cost-effective than full maintenance. It is concluded that lumen degradation failure should be considered when investigating the performance of lighting retrofit projects, as this may not only affect the energy savings, but also reduce the level of illumination, which can cause visual discomfort.

CHAPTER 5 OPTIMIZATION MODEL FOR ENERGY SAVINGS AND ECONOMIC ANALYSIS OF LED LIGHTING RETROFIT PROJECTS

5.1 CHAPTER OVERVIEW

LEDs are the most EE lighting sources for a lighting retrofit, and different countries are investigating how they can implement LEDs in buildings. However, the initial investment costs of LEDs are still a barrier to implementation. EE projects often face hurdles to access capital investments because decision-makers and funders do not have enough information about operational savings the project can provide and specific financial requirements applied to efficiency investment. This work presents an optimization model that can help decision-makers and funders to quantify energy savings and assess the economic viability of LED lighting retrofit projects. Lighting population degradation is modelled to monitor and quantify energy savings, and optimal maintenance is scheduled to maintain project performance. The net present value and payback period are used to analyse the project's economic viability. The proposed optimization is adopted in an actual residential LED lighting retrofit project implemented in South Africa to evaluate the effectiveness of the proposed model.

5.2 INTRODUCTION

Despite their significant energy savings, high efficacy, and longevity, the implementation of LED lighting systems in households is still at a low level. This is mainly due to the high initial investment. LED lighting retrofit projects often face hurdles to access capital investment because decision-makers and funders do not have credible information about the energy efficiency performance and actual energy and cost savings that the energy efficiency project can provide. To promote the implementation of LED lighting retrofit projects in residential buildings, an optimization model is formulated to give decision-makers and funders detailed information on the performance and economic viability of LED lighting retrofit projects. The optimization model is formulated to maximize energy savings and NPV and minimize the payback period.

The main contribution of this study is that an optimization model for LED lighting retrofit projects, which takes lighting system performance degradation, energy savings, and economic viability into consideration, is formulated to help decision-makers and funders quantify energy savings and assess the economic viability of LED lighting retrofit project. In the existing studies, the performance degradation of the LED lighting system and the optimization problem are not considered to help decision-makers and funders to make an informed decision. Weighting coefficients are introduced into the optimization problem to allow the decision-makers to interface with the optimization and achieve the desired performance. LED lighting population degradation due to lumen degradation failure and maintenance costs, which are usually ignored in the existing studies are considered in this study to estimate accurately energy savings and economic benefits over the evaluation period.

5.3 PROBLEM MODELLING

Energy savings over the evaluation period are modelled. The failure of the lamps, which results in a reduction in energy savings, is characterized and the surviving population is modelled to estimate the energy savings over the project's evaluation period.

Energy savings are defined as the reduction in energy consumption achieved by replacing inefficient lights with EE lights. In the lighting retrofitting project, the energy saving of each EE light is usually quantified using an M&V approach [127].

The project is evaluated over a period $[0,K]$, with a sampling interval t of 1 year. At the installation stage, time $t=0$, all installed EE lights are considered to function properly, and the energy savings are expressed as

$$W(0) = ES \times N(0), \tag{5.1}$$

where $W(0)$ is the energy savings (in kWh) at the installation stage, ES is the energy saving per retrofitted light (in kWh), and $N(0)$ is the initial installed EE lighting population.

As time goes by, the lighting population decreases owing to the failure of installed lights. Thus, the energy savings of lighting retrofit projects are calculated as the product of the number of surviving lights (lights functioning properly) and the savings of each EE light. The total energy savings over the evaluation period is given as

$$W_{total} = \sum_{t=1}^{K} ES \times N(t), \tag{5.2}$$

where $N(t)$ is the number of surviving lamps at time t.

The lighting population survival model is formulated using the Kaplan-Meier method [131].

$$\begin{aligned} S(t) &= \left(1 - \frac{d(1)}{N(1)}\right)\left(1 - \frac{d(2)}{N(2)}\right)\cdots\left(1 - \frac{d(t-1)}{N(t-1)}\right) \\ &= \prod_{j=1}^{t-1}\left(1 - \frac{d(j)}{N(j)}\right), \end{aligned} \tag{5.3}$$

where $d(j)$ is the number of lamps failed at time j. $d(j)$ is given as

$$d(j) = N(j-1)F(j), \tag{5.4}$$

where $F(j)$ is the cumulative failure distribution function. At the installation stage, time $t = 0$, the number of failed lamps $d(0) = 0$, and the Kaplan-Meier estimator of the survival function $S(0) = 1$.

As developed in the previous chapter, the cumulative failure distribution function is modelled based on lumen degradation failure. The cumulative failure distribution function is estimated using GEV distribution as it is found to be the best fit for the degradation rates of tested LUXEON Rebel, Lumileds Philips.

$$F(t) = exp\left[-\left(1 - \left(\frac{\frac{\ln\left(Lp_{th}\right)}{-t} - \iota}{\nu}\right) \times \kappa\right)^{\frac{1}{\kappa}}\right], \tag{5.5}$$

where Lp_{th} is the lumen degradation threshold (30% degradation from the initial lumen output), and ι, ν and κ are the location, scale, and shape parameters, respectively. ι, ν and κ are estimated using the L-moment estimators [124].

By using the Kaplan-Meier estimator, the surviving population is expressed as

$$N(t+1) = N(t) \times S(t). \tag{5.6}$$

By applying lamp replacement, the surviving population is expressed as

$$N(t+1) = N(t)S(t) + u(t), \tag{5.7}$$

where $u(t)$ is the number of failed lamps to be replaced. We assume the failed lamps will be replaced by the same type of lamps, which will not change the population degradation distribution.

5.4 OPTIMIZATION PROBLEM FORMULATION

An optimization problem is developed to optimize the performance and economic benefits of the EE lighting retrofit projects. The optimization problem is formulated in the subsections below.

5.4.1 Design variable

The number of lamps to be replaced is considered as the design variable of the optimization problem. Let $u(t)$ denote the number of lamps to be replaced at time t. For $t = 1, 2, \cdots, K$, U the design variable set that characterizes the optimization problem is given as

$$U = \Big[u(1), u(2), \cdots, u(K)\Big]^T. \tag{5.8}$$

The design variables are integers bound between 0 and the initial lighting population.

$$L_b = [0, \cdots, 0]^T_{K\times 1}, \text{ and } U_b = [N(0), \cdots, N(0)]^T_{K\times 1}, \tag{5.9}$$

where L_b and U_b are the lower and upper bounds of the design variables, respectively.

5.4.2 Objectives

The objective of this study is to maximize the performance and promote the implementation of EE lighting retrofit projects by analysing their economic viability. The optimization problem is formulated to maximize energy savings and NPV, and minimize the discounted payback period. When implementing energy efficiency projects, the costs involved and implementation time are one of the major factors to be considered. That is why both NPV and payback period methods are used to evaluate the economic feasibility and benefits of the studied project. NPV is used to reveal how profitable the project will be, while the payback period is used to reveal how long the project will take to recoup the funds expended in an investment.

$$\begin{cases} \min & -W_{total}, \\ \min & -NPV, \\ \min & T_p. \end{cases} \tag{5.10}$$

The weighted sum method is used to translate the optimization problem (5.10) into a single objective problem (5.11) for a subset of optimal solutions for decision making.

$$\min \quad J = -w_1 \frac{W_{total}}{\overline{W}_{total}} - w_2 \frac{NPV}{\overline{NPV}} + w_3 \frac{T_p}{\overline{T_p}}, \tag{5.11}$$

where w_1, w_2, and w_3 are the weighting coefficients, which are in range $[0,1]$, and $w_1+w_2+w_3=1$, $\overline{W}_{total}$, $\overline{NPV}$, and $\overline{T_p}$ are the maximum values of W_{total}, NPV, and T_p, respectively, used to normalize the objective function (5.11).

5.4.2.1 Net present value

The NPV is used to determine the present value of an investment by the discounted sum of all cash flows received from the project. NPV is used to analyse the profitability of the EE lighting retrofit project.

$$NPV = \sum_{t=1}^{K} \frac{C_{in}(t)}{(1+r)^t} - I_{inv}, \tag{5.12}$$

where $C_{in}(t)$ is calculated as the cash inflows (in R) minus the cash outflows (in R) at time t, r is the discount rate, and I_{inv} is the initial investment (in R). I_{inv} is given as

$$I_{inv} = N(0) \times \sigma, \tag{5.13}$$

where σ is the unit retrofit price (including the procurement, delivery, removal of an old device and installation of a new device).

The cash inflows are referred to as the money saved owing to energy and operational savings, while the cash outflows are the money spent to maintain the performance of lighting project. $C_{in}(t)$ is expressed as

$$C_{in}(t) = C_{savings}(t) + C_{rebate}(t) + C_m(t), \tag{5.14}$$

where $C_{savings}(t)$ is the cost savings (in R) obtained from energy savings, $C_m(t)$ is the cost savings (in R) from maintenance, and $C_{rebate}(t)$ is the energy saving rebate (in R). To encourage the implementation of EE lighting projects, EE lighting projects are promoted under various incentives energy efficiency programs. EE lighting retrofit projects registered under the incentive program receive an annual rebate over a certain period. $C_{savings}(t)$, $C_{rebate}(t)$, and $C_m(t)$ are given as

$$C_{savings}(t) = ES \times N(t) \times pe(t), \tag{5.15}$$

$$C_{rebate}(t) = ES \times N(t) \times r_e, \tag{5.16}$$

$$C_m(t) = C_{m_{baseline}}(t) - u(t) \times \sigma, \tag{5.17}$$

where $pe(t)$ is the price (in R) of the electricity at time t, r_e is the rebate incentive (in R/kWh), and $C_{m_{baseline}}(t)$ is the baseline maintenance cost (in R) at time t. It is assumed that the failed halogen lights would have been replaced by the same types of new halogen lights to maintain its normal function if the retrofitting of LEDs had not been implemented.

5.4.2.2 Discounted payback period

In this study, the discounted payback period is used as an indicator for the decision-makers to assess the profitability and feasibility of the EE lighting retrofit project

$$T_p = m + \frac{C_a}{C_b}, \tag{5.18}$$

where m is the last period with a negative discounted cumulative cash flow, C_a is the absolute value of discounted cumulative cash flow (in R) at the end of the m month, and C_b is the discounted cash flow (in R) during the period after m month.

5.4.3 Constraint

The objective function (5.11) is constrained by economic and physical constraints expressed in the following equations:

$$0.7 \times N(0) \leq N(t) \leq N(0) \ , \tag{5.19}$$

$$\sum_{t=1}^{K} u(t) \times \sigma \leq \psi \ , \tag{5.20}$$

$$I_{inv} + \sum_{t=1}^{K} u(t) \times \sigma \leq \rho, \tag{5.21}$$

$$T_p \leq T_{p,e}. \tag{5.22}$$

The constraint (5.19) indicates that the EE lighting retrofit project registered under an incentive energy efficiency program will earn energy savings rebates only if $N(t)$ is greater than or equal to 70% of the initial population. It is assumed that the decrease in lighting population is proportional to the illumination level. Therefore, to maintain the illumination level within the human eye's threshold, a 30% lumen degradation (commonly used in the general lighting application) is applied. Moreover, $N(t)$

should not be higher than the initial population. Constraint (5.20) indicates that the maintenance cost over the evaluation period should not exceed the allocated budget ψ for maintenance. The inequality constraint (5.21) indicates that the total cost of the lighting retrofit project should be less than or equal to the budget ρ allocated for retrofitting. The inequality constraint (5.22) indicates that the discounted payback period should be less than or equal to the expected payback period $T_{p,e}$.

5.4.4 Solution methodology

The optimization problem (5.8)-(5.22) is solved using the MIDACO (explained in Chapter 4, section 4.4.4) solver in MATLAB2017b.

5.5 CASE STUDY

An actual residential EE lighting retrofit project implemented in South Africa (given in Chapter 4, Section 4.5) is used as a case study to demonstrate the effectiveness of the formulated model. The lighting retrofit project considered is evaluated for 10 years. The electricity price is considered to increase by 8% during the evaluation period. The discount rate of 9% is considered in the calculation of NPV.

5.6 SIMULATION RESULTS ANALYSIS AND DISCUSSION

The proposed model is applied to the lighting retrofit project in the case study to demonstrate its effectiveness. As discussed in Subsection 5.4.4, to obtain the optimal solution, the optimization problem is solved using the MIDACO solver. The parameters used in the solver are given in Table 5.1. Cost and benefit assessment, and economic viability are analyzed and discussed under $w_1 = 0.4$, $w_2 = 0.4$, and $w_3 = 0.2$. The sensitivity analysis is developed to examine the influence of optimization parameters on the optimal results.

Table 5.1. Solver parameters.

Parameter name	Value
problem.o (number of objectives)	1
problem.n (number of variables)	10
problem.ni (number of integer variables)	10
problem.m (number of constraints in total)	23
problem.me (number of equality constraints)	0
problem.xl (lower bound)	$0\times$ones(1,problem.n)
problem.xu (upper bound)	$N(0)\times$ones(1,problem.n)

5.6.1 Cost assessment

The costs of implementing the case study lighting retrofit project are separated into two types of costs: (1) investment-related costs, and (2) operational-related costs. The investment costs are the costs of buying LED light bulbs, removal of halogen light bulbs, and installation of LED light bulbs. Investment costs are calculated using (5.13), and the results show that an initial investment of R 11 838 501 is required to implement the case study lighting retrofit project. The operational costs are referred to as the costs associated with maintaining the performance of the implemented lighting project. Failed lamps are optimally replaced to optimize savings and economic benefits. Figure 5.1 shows the population degradation and the optimal number of failed lamps replaced. Results show that 165 699 failed lamps will be replaced over the evaluation period at R 9 444 843. The total costs to implement and operate the case study lighting retrofit project over 10 years are R 21 283 344.

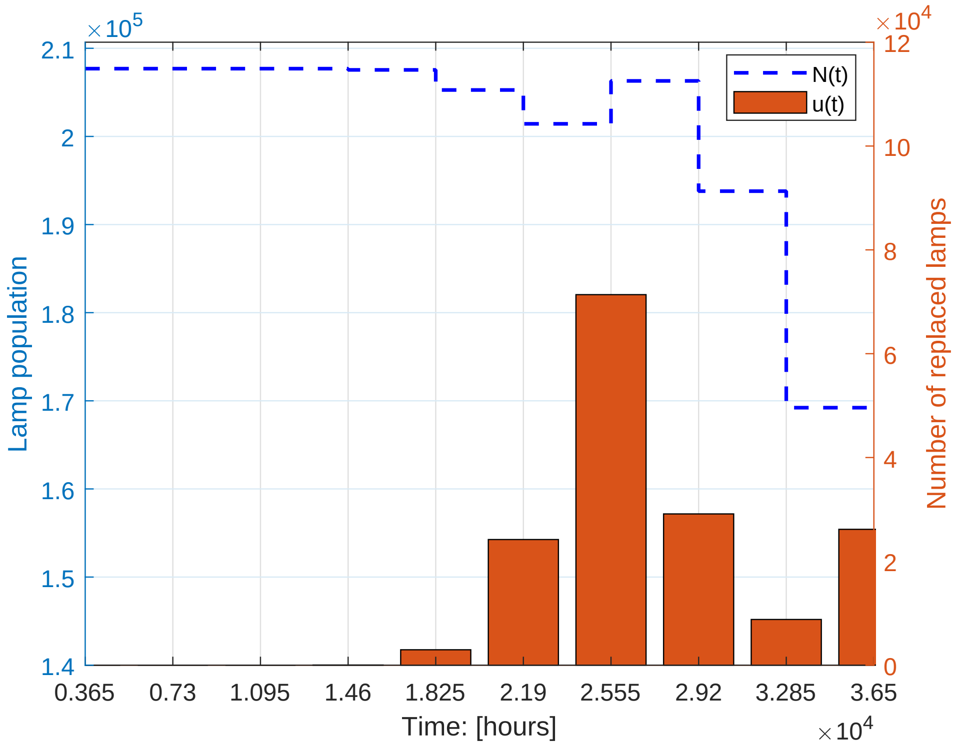

Figure 5.1. Optimal number of failed lamps to be replaced and surviving population.

5.6.2 Benefit assessment

The benefits of EE lighting retrofit projects are obtained from savings for the reduced electricity expenditure; the incentive from the EE program; and the reduction of maintenance cost. It is noticed that over time the energy savings decrease due to the lamps' failure. To maintain energy savings, optimal maintenance is scheduled and carried out. Figure 5.2 shows and compares energy savings without maintenance and when optimal maintenance is carried out. Energy savings of 291.4×10^3 MWh are obtained over the evaluation period. The cost savings obtained from the energy savings over 10 years are R 394 264 200. The benefits earned from the incentive energy efficiency programs are also considered under energy saving rebates. Over 10 years the implemented lighting retrofit project will earn energy saving rebates of R 160 270 000.

To maintain the performance of the baseline lighting system (halogen), failed halogen bulbs are assumed to be replaced by the same type of new halogen bulbs. By considering the lifetime (1 500 hours) of halogen, full maintenance will be carried out 24 times at a cost of R 174 462 120 over the evaluation period. Owing to the long lifetime of LEDs and optimal maintenance planned, LED lighting retrofit project will save R 165 017 277 from maintenance.

There is a connection between energy savings and emissions reduction. Different emissions are released during coal-fired electricity generation. The common emission in the combustion of coal is carbon dioxide (CO_2) [132]. According to Eskom[1], the CO_2 emission factor of the grid is equal to 0.94 t CO_2 e/MWh [133]. Based on energy savings, the implemented lighting retrofit project will reduce 273.92×10^3 tons of CO_2 emissions in 10 years.

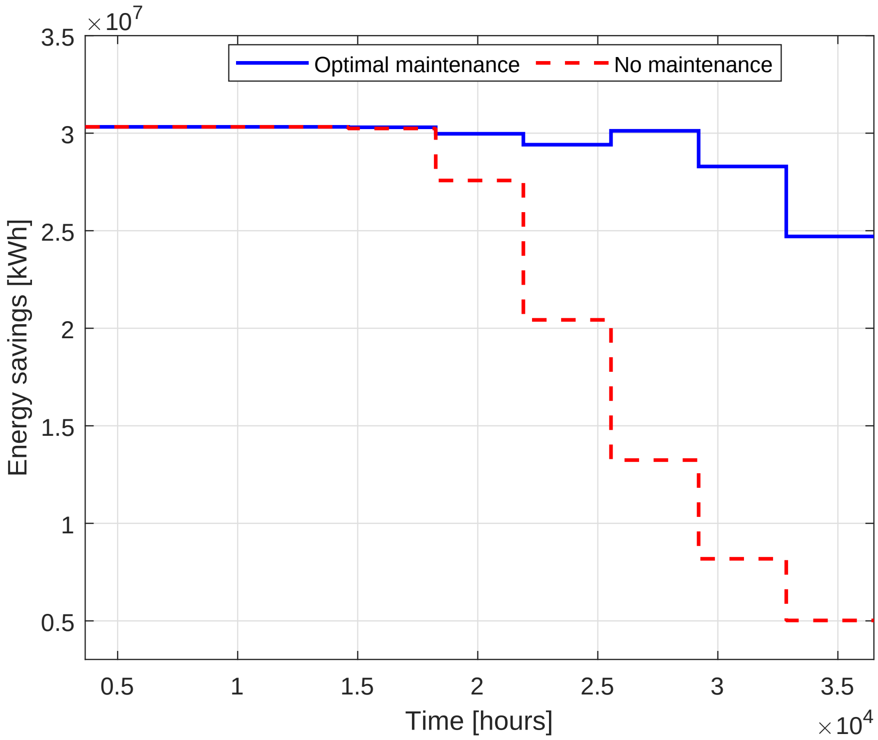

Figure 5.2. Energy savings under optimal maintenance vs. without maintenance.

5.6.3 Economic viability assessment

An economic analysis of the EE lighting retrofit project is performed. Economic viability is one of the key parameters for decision-makers and funders to accept or reject a project. The NPV and payback period methods are used to analyze the economic viability of the implemented EE lighting project. As shown in Table 5.2, the NPV of the project over 10 years is R R 453 452 000. According to the

[1]the South African's electricity utility

Table 5.2. Economic analysis of LED lighting retrofit project.

Year	Cash Inflow (R)	Cash outflow (R)	Investment (R)	NPV (R)
0	0	0	11 838 501	(11 838 501)
1	75 151 212	0	0	57 108 000
2	75 151 212	0	0	63 253 000
3	75 151 212	0	0	58 032 000
4	75 109 046	2 166	0	53 208 000
5	74 308 808	169 404	0	48 296 000
6	72 031 698	1 379 514	0	42 950 000
7	75 417 951	4 111 011	0	41 257 000
8	69 627 346	1 703 616	0	34 943 000
9	63 959 384	544 578	0	29 449 000
10	63 643 608	1 534 554	0	24 956 000
Total	**719 551 477**	**9 444 843**	**11 838 501**	**453 452 000**

NPV rule, positive NPV indicates that the project will be profitable and is worth pursuing. As per the payback period, the time it will take the project to cover the costs of the investment is calculated. The implemented lighting retrofit project will recover the money invested in it in 4 months, which is promising.

5.6.4 Sensitivity analysis

The sensitivity analysis is developed to examine the influence of certain optimization parameters on optimal results, more specifically from the weighting coefficients, maintenance budget, and lighting population.

5.6.4.1 Weighting coefficients

The weighting coefficients w_1, w_2, and w_3 in the objective function (5.11) allow trade-off between the objectives to be expressed. The project developers can vary the weighting coefficients according to their preferences. The influence of variation in the weighting coefficients on the model results is investigated by varying the weighting coefficients to $w_1 = 0.4, w_2 = 0.4, w_3 = 0.2$, $w_1 = 0.8, w_2 = 0.2, w_3 = 0$, and $w_1 = 0.2, w_2 = 0.6, w_3 = 0.2$. The simulation results are given in Table 5.3.

5.6.4.2 Retrofitting budget

The total budget of the lighting retrofit project covers the initial investment and maintenance budget provided to implement and maintain the project over the evaluation period. The total retrofitting budget may decrease in response to a fall in LED costs or may increase owing to the complexity of the project and the difficulty of adopting LEDs. The effect of oscillations in the total budget is investigated by varying the total budget to -20% and +20% concerning the basic value. The simulation results indicate that energy savings vary to 337.03×10^3 MWh when the total budget increases by 20% and to 226.6×10^3 MWh when the total budget decreases by 20%.

5.6.4.3 Lighting population

The size (large or small) of the retrofitting project can affect the energy savings and economic benefits. The influence of lighting population size is investigated in a sensitivity analysis by varying the population size to - 40% and + 40% concerning the basic value. Simulation results show that energy savings vary to 391.64×10^3 MWh when the lighting population increases by 40% and to 169.9×10^3 MWh when the lighting population decreases by 40%.

5.6.5 Discussion

Compared to the halogen lighting project, the initial investment of the LED lighting project is 63% higher. To maintain the performance of lighting system maintenance is necessary for both LEDs and halogen lights. For halogen lighting project, to maintain the performance of the lighting system, full

Table 5.3. Sensitivity analysis based on weighting coefficient choice.

	$w_1 = 0.4, w_2 = 0.4, w_3 = 0.2$	$w_1 = 0.8, w_2 = 0.2, w_3 = 0$	$w_1 = 0.2, w_2 = 0.6, w_3 = 0.2$
W_{total} (GWh)	291.4	291.63	291.13
$NPV(R)$	453 452 000	453 313 370	453 338 116
T_P	4 months	4 months	4 months

maintenance will be carried out 24 times over the evaluation period. For LED lighting retrofit project, failed lamps are optimally replaced. Owing to the long lifetime of LEDs and optimal maintenance planned, LED lighting retrofit project maintenance cost is 94% less than the halogen maintenance cost. Though the investment cost of LED lighting retrofit project is high, the operating costs are very low compared to traditional lighting projects. Table 5.4, compares the energy savings, NPV and Payback period of LED lighting retrofit project under no maintenance, full maintenance (maintenance by which all lamps will be replaced by new ones once the number of surviving lamps has reached 70% of N(0)), and optimal maintenance (failed lamps are optimally replaced).

Energy savings delivered by the LED lighting system are monitored and quantified through the surviving lighting population at each sampling interval. 75.5% of lighting energy consumption can be saved through the implementation of the case study LED lighting retrofit project and consideration of the optimization model developed. Energy saving rebates encourage investments in LED lighting retrofit projects by contributing to repaying the cost of installing LED lights. LED lighting retrofit projects not only reduce energy consumption but also reduce the emissions released during coal-fired electricity generation.

According to the NPV and payback period results, the case study LED lighting retrofit project is economically feasible and is worth pursuing. With the model formulated in this study, decision-makers and funders can quantify energy savings and assess the economic viability of an LED lighting retrofit project. Compares to the optimal maintenance plan developed in [63], the optimal maintenance plan formulated in this study takes into account the illumination level through lighting population decay based on lumen degradation, which also contributes to maintaining people's visual comfort in their homes. However, it is still challenging to quantify the visual health impact economically in this study.

Table 5.4. Energy savings and economic analysis of LED lighting retrofit project under different maintenance plans.

Maintenance plan	W_{Total} (GWh)	NPV (R)	T_p
No maintenance	177.9	195 895 000	4 months
Full maintenance	297.6	451 915 719	4 months
Optimal maintenance	291.4	453 452 000	4 months

5.7 CHAPTER SUMMARY

The current chapter continues the line of Chapter 4 by completing an economic analysis. In this chapter, an optimization model is developed to help decision-makers and funders to quantify energy savings and assess the economic viability of LED lighting retrofit projects in residential buildings. The case study results show that the substitution of halogen light bulbs with LED light bulbs could save up to 291.4 GWh of energy consumption, and reduce 273.92×10^3 tons of CO_2 emissions over a 10-year period. The optimization model formulated is effective to help decision-makers and funders to quantify the savings and assess the economic viability of the LED lighting retrofit project. Figure 5.3 compares the number of lamps to be replaced in Chapter 4 and Chapter 5.

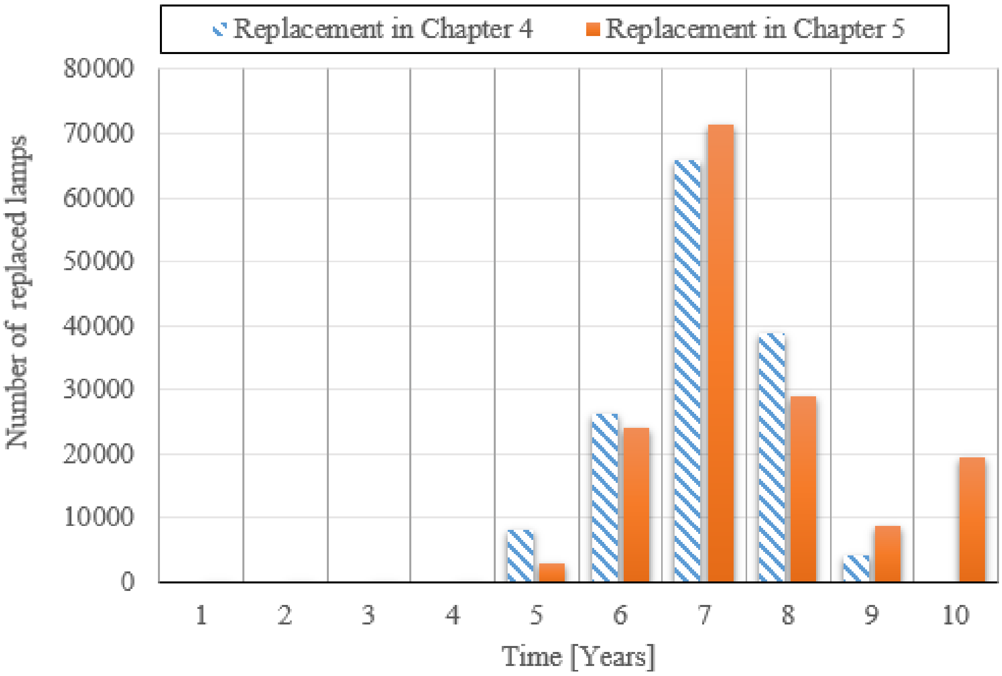

Figure 5.3. Replacements in Chapter 4 vs. replacements in Chapter 5.

CHAPTER 6 CONCLUSION AND FUTURE WORK

This thesis presents an energy savings and maintenance optimization of the EE lighting retrofit projects incorporating lumen degradation. The work done in this thesis focused on four main points : (1) investigating the impacts of users' lighting level requirements on both LEDs' life characteristics and lighting system performance overall; (2) modelling LED lamps' failure based on lumen degradation; (3) developing an optimal lighting maintenance plan that takes into account lumen degradation failure; and (4) developing an optimization model that can help decision-makers and funders obtain detailed information about the performance and operational savings that an EE lighting retrofit project can provide. An academic office and residential buildings were used as case studies to demonstrate the effectiveness and advantages of this research.

6.1 CONCLUSION

The impact of users' lighting level requirements on LEDs' life characteristics and lighting system performance is investigated by modelling the luminous flux degradation of LEDs. This degradation can be increased or decreased by varying operating conditions such as driving current and elevated temperatures. The driving current varies mainly depending on the users' lighting level requirements. The results showed that the users' light level requirements affect the luminous flux degradation and lifetime of LEDs significantly. Luminous flux degradation is increased when the user's light level requirements are above the light level required under normal operating conditions and is decreased when the users' light level requirements are below the light level required under normal operating conditions. Increased luminous flux degradation shortens the lifetime of LEDs and decreased luminous flux degradation extends the lifetime. It is also noticed that luminous flux degradation affects the energy savings of the EE lighting retrofit project considerably. Increased luminous flux degradation decreases energy savings and decreased luminous flux degradation increases energy savings. It is concluded that users' lighting level requirements affect the life characteristics and lighting system performance of a LED-based lighting system significantly.

Lumen degradation, entailing the natural decrease in light output that occurs as a lamp operates over time, is modelled in this work. Before lamps burn out, the light output gradually decreases over time. This means that before lamps burn out, the illumination level may be inadequate to carry out a task safely. For LEDs, the burnout failure is not significant owing to their longevity. In this work, the failure of LEDs is modelled based on lumen degradation, and the surviving population in LED-based lighting retrofit projects is predicted. Lumen degradation failure is modelled by analysing the statistical properties of the degradation rates of LEDs and different probability distributions are tested to find the best distribution to fit the samples' degradation rates. Kolmogorov Smirnov, Anderson Darling, and Chi-Squared goodness fit tests are used to determine the best fit of samples' degradation rates, and the best fit distribution is used to calculate the cumulative probability of failure distribution and model the lumen degradation failure. Thereafter, the lumen degradation failure model is used to characterize the surviving population by using the Kaplan-Meier method. When lumen output degradation is modelled and monitored, it helps to maintain users' lighting level requirements and control lighting system performance. It is concluded that lumen degradation failure should be considered when investigating the performance of EE lighting retrofit projects, as this may not only affect the energy savings but also reduce the level of illumination, which can cause visual discomfort.

A maintenance plan is developed to optimize the performance and maintenance costs of EE lighting retrofit projects. The maintenance plan formulated considers the lumen degradation of retrofitted lights. The optimization problem is formulated to maximize energy savings and minimize maintenance costs. The optimization problem is solved using the MIDACO solver in MATLAB. The problem is solved to find the optimal number of failed lamps to be replaced and to determine maintenance schedules. The failed lamps are optimally replaced based on a minimum number of surviving lamps required to maintain adequate illumination levels, energy savings, and maintenance budget limits.

Despite their significant energy savings, high efficacy, and long lifetime, the implementation of LED lighting systems in households is still at a low level. This is mainly due to the high initial investment. LED lighting retrofit projects often face hurdles to access capital investment because decision-makers and funders have poor information about the energy efficiency performance and operational savings that LED lighting retrofit projects can provide, and the specific financial requirements applied to efficiency investments. To promote the implementation of LED lighting retrofit projects in residential buildings, an optimization model is formulated to give decision-makers and funders detailed information about the performance and operational savings that EE lighting retrofit projects can provide, and their economic viability. The optimization model is formulated to maximize energy savings and NPV, and minimize the discounted payback period. According to the NPV and payback period results, the studied LED lighting retrofit project is economically viable and is worth pursuing. Using the model formulated in this work, decision-makers and funders can quantify energy savings and analyse the economic viability of an LED lighting retrofit project. This will encourage and promote the implementation of LED lighting retrofit projects.

The main contributions of this research can be summarized as follows:

1. The formulation of a luminous flux degradation model that takes into account users' lighting level requirements.
2. The formulation of a LED lumen degradation failure model based on the statistical properties of lumen degradation rates.
3. The formulation of an energy-maintenance optimal model that takes into account luminous flux degradation. This model maximizes energy savings and minimizes maintenance costs.
4. The development of an optimization model for EE lighting retrofit projects, which takes lighting system performance degradation, savings, and economic benefits into consideration to promote the implementation of LED lighting retrofit projects.

6.2 FUTURE WORK

This research can be improved by considering the following aspects:

1. The impact of daylight on lumen degradation and LEDs' life characteristics should be investigated, especially for buildings operating mostly during the day.
2. In this research lumen degradation failure is considered in developing an effective maintenance plan; in future research, both lumen degradation and burnout failures could be considered.

3. Maintenance plans in this research are developed under the periodic preventive maintenance policy, but maintenance can also be developed under different policies including an age-dependent preventive maintenance policy, failure limit policy, and sequential preventive maintenance policy.
4. Work carried out in this research can be expanded to other types of EE lighting retrofit projects. And life cost parameters may be taken into consideration in future work.

REFERENCES

[1] R. N. Keneilwe Ratshomo, "Directorate energy data collection, management and analysis," South African Energy Department, Tech. Rep., 2018.

[2] P. Bertoldi and B. Atanasiu, "Residential lighting consumption and saving potential in the enlarged EU," in *Proceedings of 4th International Conference on Energy Efficiency in Domestic Appliances and Lighting (EEDAL'06)*. Citeseer, 2006, pp. 21–23.

[3] K. Amasyali and N. M. El-Gohary, "A review of data-driven building energy consumption prediction studies," *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 1192–1205, 2018.

[4] F. P. Vahl, L. M. Campos, and N. Casarotto Filho, "Sustainability constraints in techno-economic analysis of general lighting retrofits," *Energy and Buildings*, vol. 67, pp. 500–507, 2013.

[5] P. Belany, A. Bolf, M. Novak, M. Roch, and A. Otcenasova, "Decreasing the power consumption of buildings with utilization of lighting control," in *2018 ELEKTRO*. IEEE, 2018, pp. 1–6.

[6] A. De Almeida, B. Santos, B. Paolo, and M. Quicheron, "Solid state lighting review–potential and challenges in Europe," *Renewable and Sustainable Energy Reviews*, vol. 34, pp. 30–48, 2014.

[7] C. Valdez-Flores and R. M. Feldman, "A survey of preventive maintenance models for stochastically deteriorating single-unit systems," *Naval Research Logistics (NRL)*, vol. 36, no. 4, pp. 419–446, 1989.

[8] M.-H. Chang, D. Das, P. Varde, and M. Pecht, "Light emitting diodes reliability review," *Microelectronics Reliability*, vol. 52, no. 5, pp. 762–782, 2012.

[9] S.-C. Yang, P. Lin, C.-P. Wang, S. B. Huang, C.-L. Chen, P.-F. Chiang, A.-T. Lee, and M.-T. Chu, "Failure and degradation mechanisms of high-power white light emitting diodes," *Microelectronics Reliability*, vol. 50, no. 7, pp. 959–964, 2010.

[10] F.-K. Wang and Y.-C. Lu, "Useful lifetime analysis for high-power white LEDs," *Microelectronics Reliability*, vol. 54, no. 6-7, pp. 1307–1315, 2014.

[11] S. Ishizaki, H. Kimura, and M. Sugimoto, "Lifetime estimation of high power white LEDs," *Journal of Light & Visual Environment*, vol. 31, no. 1, pp. 11–18, 2007.

[12] S. Andrew, K. and C. T. Albert, H., *Maintenance, Replacement, and Reliability: Theory and Applications: Second Edition*. Taylor & Francis Group, 2013.

[13] S.-H. Ding and S. Kamaruddin, "Maintenance policy optimization: literature review and directions," *The International Journal of Advanced Manufacturing Technology*, vol. 76, no. 5-8, pp. 1263–1283, 2015.

[14] R. J. Tersine, *Production/Operations Management: Concepts, Structure and Analysis*. North Holland, 1985, vol. 1.

[15] A. Barros, A. Grall, and C. Berenguer, "Joint modelling and optimization of monitoring and maintenance performance for a two-unit parallel system," *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, vol. 221, no. 1, pp. 1–11, 2007.

[16] M. Braglia, M. Frosolini, and R. Montanari, "Fuzzy criticality assessment model for failure modes and effects analysis," *International Journal of Quality & Reliability Management*, vol. 20, no. 4, pp. 503–524, 2003.

[17] M. Cai, D. Yang, K. Tian, W. Chen, X. Chen, P. Zhang, X. Fan, and G. Zhang, "A hybrid prediction method on luminous flux maintenance of high-power LED lamps," *Applied Thermal*

Engineering, vol. 95, pp. 482–490, 2016.

[18] C. Qian, X. Fan, J. Fan, C. A. Yuan, and G. Zhang, "An accelerated test method of luminous flux depreciation for LED luminaires and lamps," *Reliability Engineering & System Safety*, vol. 147, pp. 84–92, 2016.

[19] X. Qu, H. Wang, X. Zhan, F. Blaabjerg, and H. S.-H. Chung, "A lifetime prediction method for LEDs considering real mission profiles," *IEEE Transactions on Power Electronics*, vol. 32, no. 11, pp. 8718–8727, 2017.

[20] D. L. DiLaura, K. W. Houser, R. G. Mistrick, and G. R. Steffy, *The lighting handbook: Reference and application*. Illuminating Engineering Society of North America New York, 2011.

[21] M. Azmatullah, *Lighting Systems and Their Design*, A. M. A. M. M.Arch, Ed. Design, 2014.

[22] P. Thorns, "Light and lighting - Lighting of workplaces. Part 1: Indoor work places," ZLD, Tech. Rep., 2010.

[23] M. S. Islam, N. A. Chowdhury, A. K. Sakil, A. Khandakar, A. Iqbal, and H. Abu-Rub, "Power quality effect of using incandescent, fluorescent, CFL and LED lamps on utility grid," in *Smart Grid and Renewable Energy (SGRE), 2015 First Workshop*. IEEE, 2015, pp. 1–5.

[24] J. F. Waymouth, *Electrical Discharge Lamps*. The MIT Press, 1971.

[25] G. G. Lister, J. E. Lawler, W. P. Lapatovich, and V. A. Godyak, "The physics of discharge lamps," *Reviews of Modern Physics*, vol. 76, no. 2, p. 541, 2004.

[26] L. Han and N. Narendran, "An accelerated test method for predicting the useful life of an LED driver," *IEEE Transactions on Power Electronics*, vol. 26, no. 8, pp. 2249–2257, 2011.

[27] L. Tobias, G. Vavaroutsos *et al.*, *Retrofitting office buildings to be green and energy-efficient: Optimizing building performance, tenant satisfaction, and financial return*. Urban Land

Institute Washington, DC, 2009.

[28] P. Ihm, A. Nemri, and M. Krarti, “Estimation of lighting energy savings from daylighting,” *Building and Environment*, vol. 44, no. 3, pp. 509–514, 2009.

[29] C. F. Reinhart, “Lightswitch-2002: A model for manual and automated control of electric lighting and blinds,” *Solar Energy*, vol. 77, no. 1, pp. 15–28, 2004.

[30] X. Guo, D. Tiller, G. Henze, and C. Waters, “The performance of occupancy-based lighting control systems: A review,” *Lighting Research & Technology*, vol. 42, no. 4, pp. 415–431, 2010.

[31] Natural Resources Canada CanmetENERGY, “Overview of Different Measurement and Verification (M&V) Protocols,” ECONOLER, Tech. Rep., 2008.

[32] N. Shishegar and M. Boubekri, “Quantifying electrical energy savings in offices through installing daylight responsive control systems in hot climates,” *Energy and Buildings*, vol. 153, pp. 87–98, 2017.

[33] S. Ismail and J. M. Rogerson, “Retrofitting hotels: evidence from the Protea Hospitality Group of hotels within Gauteng, South Africa,” *University of Johannesburg*, 2016.

[34] E. Shen, J. Hu, and M. Patel, “Energy and visual comfort analysis of lighting and daylight control strategies,” *Building and Environment*, vol. 78, pp. 155–170, 2014.

[35] E. Uken, G. Bevan, and R. Smith, “LED tube retrofits for fluorescent lighting in offices,” in *Industrial and Commercial Use of Energy Conference (ICUE), 2013 Proceedings of the 10th*. IEEE, 2013, pp. 1–4.

[36] T. Mahlia, H. A. Razak, and M. Nursahida, “Life cycle cost analysis and payback period of lighting retrofit at the University of Malaya,” *Renewable and Sustainable Energy Reviews*, vol. 15, no. 2, pp. 1125–1132, 2011.

[37] D. H. Li, K. L. Cheung, S. L. Wong, and T. N. Lam, “An analysis of energy-efficient light fittings and lighting controls,” *Applied Energy*, vol. 87, no. 2, pp. 558–567, 2010.

[38] D. H. Li, A. H. Mak, W. W. Chan, and C. C. Cheng, “Predicting energy saving and life-cycle cost analysis for lighting and daylighting schemes,” *International Journal of Green Energy*, vol. 6, no. 4, pp. 359–370, 2009.

[39] B. Roisin, M. Bodart, A. Deneyer, and P. D’herdt, “Lighting energy savings in offices using different control systems and their real consumption,” *Energy and Buildings*, vol. 40, no. 4, pp. 514–523, 2008.

[40] A. D. Galasiu, G. R. Newsham, C. Suvagau, and D. M. Sander, “Energy saving lighting control systems for open-plan offices: a field study,” *Leukos*, vol. 4, no. 1, pp. 7–29, 2007.

[41] D. H. Li, T. N. Lam, and S. Wong, “Lighting and energy performance for an office using high frequency dimming controls,” *Energy Conversion and Management*, vol. 47, no. 9-10, pp. 1133–1145, 2006.

[42] T. Mahlia, M. Said, H. Masjuki, and M. Tamjis, “Cost-benefit analysis and emission reduction of lighting retrofits in residential sector,” *Energy and Buildings*, vol. 37, no. 6, pp. 573–578, 2005.

[43] D. H. Li and J. C. Lam, “Evaluation of lighting performance in office buildings with daylighting controls,” *Energy and Buildings*, vol. 33, no. 8, pp. 793–803, 2001.

[44] B. Von Neida, D. Manicria, and A. Tweed, “An analysis of the energy and cost savings potential of occupancy sensors for commercial lighting systems,” *Journal of the Illuminating Engineering Society*, vol. 30, no. 2, pp. 111–125, 2001.

[45] W. D. Van Driel, X. Fan, and G. Q. Zhang, *Solid State Lighting Reliability Part 2: Components to Systems*. Springer, 2017, vol. 3.

[46] N. Gorjian, L. Ma, M. Mittinty, P. Yarlagadda, and Y. Sun, "A review on degradation models in reliability analysis," in *Engineering Asset Lifecycle Management*. Springer, 2010, pp. 369–384.

[47] A. Christensen and S. Graham, "Thermal effects in packaging high power light emitting diode arrays," *Applied Thermal Engineering*, vol. 29, no. 2-3, pp. 364–371, 2009.

[48] E. F. Schubert and J. K. Kim, "Solid-state light sources getting smart," *Science*, vol. 308, no. 5726, pp. 1274–1278, 2005.

[49] S. Chhajed, Y. Xi, Y.-L. Li, T. Gessmann, and E. Schubert, "Influence of junction temperature on chromaticity and color-rendering properties of trichromatic white-light sources based on light-emitting diodes," *Journal of Applied Physics*, vol. 97, no. 5, p. 054506, 2005.

[50] M. Y. Mehr, W. D. van Driel, and G. K. Zhang, "Progress in understanding color maintenance in solid-state lighting systems," *Engineering*, vol. 1, no. 2, pp. 170–178, 2015.

[51] P. O'Connor and A. Kleyner, *Practical Reliability Engineering*, J. W. . Sons, Ed. John Wiley & Sons, 2012.

[52] UNFCCC, "Approved small scale methodology AMS II.C.: demand-side energy efficiency activities for specific technologies." UNFCCC, Tech. Rep., Version 14.0; 2012b.

[53] C. Granda, "Case study: The IFC/GEF Poland Efficient Lighting Project," in *Right Light 4. Proceedings of the 4th European Conference on Energy-Efficient Lighting*, 1997.

[54] B. Delmas, "Pierre-François Verhulst et la loi logistique de la population," *Mathématiques et Sciences Humaines. Mathematics and Social Sciences*, no. 167, 2004.

[55] H. Carstens, X. Xia, and X. Ye, "Improvements to longitudinal Clean Development Mechanism sampling designs for lighting retrofit projects," *Applied Energy*, vol. 126, pp. 256–265, 2014.

[56] H. Carstens, X. Xia, J. Zhang, and X. Ye, "Characterising compact fluorescent lamp population decay," in *AFRICON*. IEEE, 2013, pp. 1–5.

[57] Philips Lumileds, "IESNA LM-80 Test Report," Stunning Lighting Technology CO., Ltd, Tech. Rep., 2012.

[58] J. Fan, K.-C. Yung, and M. Pecht, "Lifetime estimation of high-power white LED using degradation-data-driven method," *IEEE Transactions on Device and Materials Reliability*, vol. 12, no. 2, pp. 470–477, 2012.

[59] R. A. Guisso, M. F. Righi, E. M. Sá, R. A. Pinto, V. C. Bender, and T. B. Marchesan, "An Extended Design Methodology for LED Lighting Systems Including Lifetime Estimation," *IEEE Transactions on Electron Devices*, vol. 63, no. 12, pp. 4852–4859, 2016.

[60] S.-D. Huang, L. Zhou, G.-Z. Cao, H.-Y. Liu, Y.-M. Hu, G. Jing, M.-G. Cao, W.-P. Xiao, and Y. Liu, "A novel multiple-stress-based predictive model of LEDs for rapid lifetime estimation," *Microelectronics Reliability*, vol. 78, pp. 46–52, 2017.

[61] J. L. Davis, "System reliability model for solid-state lighting (SSL) luminaires," RTI International, Research Triangle Park, NC (United States), Tech. Rep., 2017.

[62] X. Ye, X. Xia, and J. Zhang, "Optimal sampling plan for clean development mechanism energy efficiency lighting projects," *Applied Energy*, vol. 112, pp. 1006–1015, 2013.

[63] X. Ye, X. Xia, L. Zhang, and B. Zhu, "Optimal maintenance planning for sustainable energy efficiency lighting retrofit projects by a control system approach," *Control Engineering Practice*, vol. 37, pp. 1–10, 2015.

[64] B. Wang, X. Xia, and J. Zhang, "A multi-objective optimization model for the life-cycle cost analysis and retrofitting planning of buildings," *Energy and Buildings*, vol. 77, pp. 227–235, 2014.

[65] X. Ye and X. Xia, "Optimal metering plan for measurement and verification on a lighting case study," *Energy*, vol. 95, pp. 580–592, 2016.

[66] F. Ruknudeen and S. Asokan, “Application of particle filter to on-board life estimation of LED lights,” *IEEE Photonics Journal*, vol. 9, no. 3, pp. 1–16, 2017.

[67] P. Nayak, A. N. Padmasali, and S. G. Kini, “Life estimation of high power LED using distribution based reliability analysis,” in *2017 2nd IEEE International Conference on Recent Trends in Electronics, Information & Communication Technology (RTEICT)*. IEEE, 2017, pp. 1626–1631.

[68] H.-L. Ke, J. Hao, J.-H. Tu, P.-X. Miao, C.-Q. Wang, J.-Z. Cui, Q. Sun, and R.-T. Sun, “Lumen degradation analysis of LED lamps based on the subsystem isolation method,” *Applied Optics*, vol. 57, no. 4, pp. 849–854, 2018.

[69] M. Cai, D. Yang, K. Tian, P. Zhang, X. Chen, L. Liu, and G. Zhang, “Step-stress accelerated testing of high-power LED lamps based on subsystem isolation method,” *Microelectronics Reliability*, vol. 55, no. 9-10, pp. 1784–1789, 2015.

[70] T.-R. Tsai, Y. Lio, and N. Jiang, “Optimal decisions on the accelerated degradation test plan under the Wiener process,” *Quality Technology & Quantitative Management*, vol. 11, no. 4, pp. 461–470, 2014.

[71] P. Lall, H. Zhang, and L. Davis, “Assessment of lumen degradation and remaining life of LEDs using particle filter,” in *ASME 2013 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems*. American Society of Mechanical Engineers, 2013, pp. V001T04A024–V001T04A024.

[72] F.-K. Wang and T.-P. Chu, “Lifetime predictions of LED-based light bars by accelerated degradation test,” *Microelectronics Reliability*, vol. 52, no. 7, pp. 1332–1336, 2012.

[73] W. Geraerds, “The cost of downtime for maintenance: preliminary considerations,” *EUT-BDK report. Dept. of Industrial Engineering and Management Science*, vol. 11, 1984.

[74] A. Van Horenbeek, L. Pintelon, and P. Muchiri, “Maintenance optimization models and criteria,” *International Journal of System Assurance Engineering and Management*, vol. 1, no. 3, pp.

189–200, 2010.

[75] H. Wang, “A survey of maintenance policies of deteriorating systems,” *European Journal of Operational Research*, vol. 139, no. 3, pp. 469–489, 2002.

[76] H. Block, W. Borges, and T. Savits, “A general age replacement model with minimal repair,” *Naval Research Logistics (NRL)*, vol. 35, no. 5, pp. 365–372, 1988.

[77] S.-H. Sheu, C.-M. Kuo, and T. Nakagawa, “Extended optimal age replacement policy with minimal repair,” *RAIRO-Operations Research*, vol. 27, no. 3, pp. 337–351, 1993.

[78] X.-G. Liu, V. Makis, and A. K. Jardine, “A replacement model with overhauls and repairs,” *Naval Research Logistics (NRL)*, vol. 42, no. 7, pp. 1063–1079, 1995.

[79] H. Wang and H. Pham, “Some maintenance models and availability with imperfect maintenance in production systems,” *Annals of Operations Research*, vol. 91, pp. 305–318, 1999.

[80] T. Nakagawa, “A summary of periodic replacement with minimal repair at failure,” *Journal of the Operations Research Society of Japan*, vol. 24, no. 3, pp. 213–228, 1981.

[81] V. Jayabalan and D. Chaudhuri, “Replacement policies: a near optimal algorithm,” *IEEE transaction*, vol. 27, no. 6, pp. 784–788, 1995.

[82] C. Love and R. Guo, “Utilizing Weibull failure rates in repair limit analysis for equipment replacement/preventive maintenance decisions,” *Journal of the Operating Research Society*, vol. 47, no. 11, pp. 1366–1376, 1996.

[83] A. Birolini, *Reliability Engineering*. Springer, 2007, vol. 5.

[84] D. Lin, M. J. Zuo, and R. C. Yam, “General sequential imperfect preventive maintenance models,” *International Journal of Reliability, Quality and Safety Engineering*, vol. 7, no. 03, pp. 253–266, 2000.

[85] L. Dieulle, C. Bérenguer, A. Grall, and M. Roussignol, “Sequential condition-based maintenance scheduling for a deteriorating system,” *European Journal of Operational Research*, vol. 150, no. 2, pp. 451–461, 2003.

[86] H. P. Hongzhou Wang, *Reliability and Optimal Maintenance*. Springer Science & Business Media, 2006.

[87] T. Nakagawa, *Maintenance Theory of Reliability*. Springer Science & Business Media, 2006.

[88] T. Nowakowski and S. Werbińka, “On problems of multicomponent system maintenance modelling,” *International Journal of Automation and Computing*, vol. 6, no. 4, p. 364, 2009.

[89] S.-H. Sheu and J.-P. Jhang, “A generalized group maintenance policy,” *European Journal of Operational Research*, vol. 96, no. 2, pp. 232–247, 1997.

[90] F. Van der Duyn Schouten, “Maintenance policies for multicomponent systems: An overview,” in *Reliability and Maintenance of Complex Systems*. Springer, 1996, pp. 117–136.

[91] R. Laggoune, A. Chateauneuf, and D. Aissani, “Opportunistic policy for optimal preventive maintenance of a multi-component system in continuous operating units,” *Computers & Chemical Engineering*, vol. 33, no. 9, pp. 1499–1510, 2009.

[92] X. Zhou, L. Xi, and J. Lee, “A dynamic opportunistic maintenance policy for continuously monitored systems,” *Journal of Quality in Maintenance Engineering*, vol. 12, no. 3, pp. 294–305, 2006.

[93] H. Pham and H. Wang, “Optimal (τ, T) opportunistic maintenance of ak-out-of-n: G system with imperfect PM and partial failure,” *Naval Research Logistics (NRL)*, vol. 47, no. 3, pp. 223–239, 2000.

[94] A. Robertson and A. Jones, “Pay day,” *Plant Engineering and Maintenance, Vol. 28, No. 9, pp. 18-25,*, 2004.

[95] K. B. Marais and J. H. Saleh, "Beyond its cost, the value of maintenance: an analytical framework for capturing its net present value," *Reliability Engineering & System Safety*, vol. 94, no. 2, pp. 644–657, 2009.

[96] A. W. Labib, "World-class maintenance using a computerised maintenance management system," *Journal of Quality in Maintenance Engineering*, vol. 4, no. 1, pp. 66–75, 1998.

[97] B. A. Lugtigheid Diederik and J. Andrew, "Modelling repairable system reliability with explanatory variables and repair and maintenance actions," *IMA Journal of Management Mathematics*, vol. 15, no. 2, pp. 89–110, 2004.

[98] E. Borgonovo, M. Marseguerra, and E. Zio, "A Monte Carlo methodological approach to plant availability modeling with maintenance, aging and obsolescence," *Reliability Engineering & System Safety*, vol. 67, no. 1, pp. 61–73, 2000.

[99] K. A. Kobbacy, "Artificial intelligence in maintenance," in *Complex System Maintenance Handbook*. Springer, 2008, pp. 209–231.

[100] M. Marseguerra and E. Zio, "Optimizing maintenance and repair policies via a combination of genetic algorithms and Monte Carlo simulation," *Reliability Engineering & System Safety*, vol. 68, no. 1, pp. 69–83, 2000.

[101] T. Rosqvist, K. Laakso, and M. Reunanen, "Value-driven maintenance planning for a production plant," *Reliability Engineering & System Safety*, vol. 94, no. 1, pp. 97–110, 2009.

[102] S. Pohekar and M. Ramachandran, "Application of multi-criteria decision making to sustainable energy planning: a review," *Renewable and Sustainable Energy Reviews*, vol. 8, no. 4, pp. 365–381, 2004.

[103] E. Shayesteh, J. Yu, and P. Hilber, "Maintenance optimization of power systems with renewable energy sources integrated," *Energy*, vol. 149, pp. 577–586, 2018.

[104] B. R. Sarker and T. I. Faiz, “Minimizing maintenance cost for offshore wind turbines following multi-level opportunistic preventive strategy,” *Renewable Energy*, vol. 85, pp. 104–113, 2016.

[105] B. Wang and X. Xia, “Optimal maintenance planning for building energy efficiency retrofitting from optimization and control system perspectives,” *Energy and Buildings*, vol. 96, pp. 299–308, 2015.

[106] G. Kumar and J. Maiti, “Modeling risk based maintenance using fuzzy analytic network process,” *Expert Systems with Applications*, vol. 39, no. 11, pp. 9946–9954, 2012.

[107] M. Bashiri, H. Badri, and T. H. Hejazi, “Selecting optimum maintenance strategy by fuzzy interactive linear assignment method,” *Applied Mathematical Modelling*, vol. 35, no. 1, pp. 152–164, 2011.

[108] S. H. Chung, H. C. Lau, G. T. Ho, and W. H. Ip, “Optimization of system reliability in multi-factory production networks by maintenance approach,” *Expert Systems with Applications*, vol. 36, no. 6, pp. 10 188–10 196, 2009.

[109] G. Morcous and Z. Lounis, “Maintenance optimization of infrastructure networks using genetic algorithms,” *Automation in Construction*, vol. 14, no. 1, pp. 129–142, 2005.

[110] B. Al-Najjar and I. Alsyouf, “Selecting the most efficient maintenance approach using fuzzy multiple criteria decision making,” *International Journal of Production Economics*, vol. 84, no. 1, pp. 85–100, 2003.

[111] C. K. Mechefske and Z. Wang, “Using fuzzy linguistics to select optimum maintenance and condition monitoring strategies,” *Mechanical Systems and Signal Processing*, vol. 15, no. 6, pp. 1129–1140, 2001.

[112] J. Barata, C. G. Soares, M. Marseguerra, and E. Zio, “Simulation modelling of repairable multi-component deteriorating systems for on condition maintenance optimisation,” *Reliability Engineering & System Safety*, vol. 76, no. 3, pp. 255–264, 2002.

[113] A. Ikuzwe, X. Ye, and X. Xia, "Energy-maintenance optimization for retrofitted lighting system incorporating luminous flux degradation to enhance visual comfort," *Applied Energy*, vol. 261, p. 114379, 2020.

[114] R. T. Marler and J. S. Arora, "The weighted sum method for multi-objective optimization: New insights," *Structural and Multidisciplinary Optimization*, vol. 41, no. 6, pp. 853–862, 2010.

[115] K. R. Egan M David, *Concepts in Architectural Lighting*. McGraw-Hill New York, 1983, vol. 1110.

[116] A. Ikuzwe, X. Xia, and X. Ye, "Maintenance optimization incorporating lumen degradation failure for energy-efficient lighting retrofit projects," *Applied Energy*, vol. 267, p. 115003, 2020.

[117] A. Bierman, J. P. Freyssinier, Y. Zhu, N. Narendran, "LED Testing Standards Overview," Lighting Research Center, Rensselaer Polytechnic Institute, Troy, NY, USA, Tech. Rep., 2012.

[118] V. R. B. De Oliveira and E. A. Colosimo, "Comparison of methods to estimate the time-to-failure distribution in degradation tests," *Quality and Reliability Engineering International*, vol. 20, no. 4, pp. 363–373, 2004.

[119] W. D. Van Driel, X. Fan, and G. Q. Zhang, *Solid State Lighting Reliability Part 2: Components to Systems*. Springer International Publishing, New York, 2017, vol. 3.

[120] E. S. Martins and J. R. Stedinger, "Generalized maximum-likelihood generalized extreme-value quantile estimators for hydrologic data," *Water Resources Research*, vol. 36, no. 3, pp. 737–744, 2000.

[121] R. G. Miller Jr, *Survival Analysis*. John Wiley & Sons; 2 Edition, 2011, vol. 66.

[122] P. Ailliot, C. Thompson, and P. Thomson, "Mixed methods for fitting the GEV distribution," *Water Resources Research*, vol. 47, no. 5, 2011.

[123] J. R. Hosking, J. R. Wallis, and E. F. Wood, “Estimation of the generalized extreme-value distribution by the method of probability-weighted moments,” *Technometrics*, vol. 27, no. 3, pp. 251–261, 1985.

[124] J. R. Hosking, “L-moments: analysis and estimation of distributions using linear combinations of order statistics,” *Journal of the Royal Statistical Society. Series B (Methodological)*, pp. 105–124, 1990.

[125] Q. Wang, “Direct sample estimators of L -moments,” *Water Resources Research*, vol. 32, no. 12, pp. 3617–3619, 1996.

[126] J. Hosking and J. Wallis, “A comparison of unbiased and plotting-position estimators of L-moments,” *Water Resources Research*, vol. 31, no. 8, pp. 2019–2025, 1995.

[127] X. Xia and J. Zhang, “Mathematical description for the measurement and verification of energy efficiency improvement,” *Applied Energy*, vol. 111, pp. 247–256, 2013.

[128] M. Schleuter and M. Munetomo, “Introduction to MIDACO-SOLVER software,” Tech. Rep., 2013.

[129] ASSAF, “The state of research, development and innovation of electrical energy efficiency technologies in South Africa,” Academy of Science of South Africa, Tech. Rep., 2017.

[130] P. Lynn, “Principles of Sampling,” *Research Methods for Postgraduates*, vol. 2, pp. 185–194, 2002.

[131] K. J. Jager, P. C. Van Dijk, C. Zoccali, and F. W. Dekker, “The analysis of survival data: the Kaplan-Meier method,” *Kidney International*, vol. 74, no. 5, pp. 560–565, 2008.

[132] S. Ding, Y.-G. Dang, X.-M. Li, J.-J. Wang, and K. Zhao, “Forecasting chinese CO2 emissions from fuel combustion using a novel grey multivariable model,” *Journal of Cleaner Production*, vol. 162, pp. 1527–1538, 2017.

[133] S. Rippon and B. Design, "University of Cape Town Carbon Footprint Report 2013," *University of Cape Town*, 2014.