CRITERIA FOR SELECTING LED LUMINAIRES

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Abstract

Fluorescent tubes and compact fluorescent lamps (CFL) were the dominant artificial light source for so many years in domestic, commercial and industrial contexts. In the recent years Light Emitting Diodes (LEDs) have gained much popularity with the proven energy and economic benefits and are now used in almost every lighting application. Other benefits include compact size, long service life, ease of maintenance and instant-on quality. Ease of dimming and controlling of LEDs set forth further energy savings. Currently there is an increasing trend for using LED luminaires in many commercial buildings and this has led to form a huge demand for LED luminaires and a huge market competition between the lighting solution suppliers.

When the LED bulbs were first introduced to the Sri Lankan market, the retail market was flooded with many low-quality products and most of the domestic consumers could not reap the maximum benefit. Same goes for the LED luminaires. Since these LED luminaires are used in thousands of quantities in commercial buildings hoping to last for decades, if not wisely chosen, huge performance and economic losses have to be endured.

With the absence of a national guideline to choose LED fixtures there is an ambiguity among lighting designers and clients when choosing the most suitable luminaire from the wide range of LED luminaires available in Sri Lankan market. Therefore, the intention of this research was to develop general criteria that can be used for choosing the most suitable LED luminaire for a given building.

Worldwide building codes and rating systems were studied to identify the minimum performance level expected from the LED luminaires in other countries. LED luminaires in Sri Lankan and foreign markets were technically evaluated. Technical specifications of LED luminaires were obtained from manufacturers' websites and the market prices were obtained from suppliers.

Findings of this research include the evolution of lighting requirements imposed by building codes, performance status of LED luminaires available in Sri Lanka market, general criteria for choosing LED luminaires and justification of the proposed criteria with an example application.

Keywords: *light-emitting diode (LED), solid-state lighting, Luminaire, Lighting design, Lamp lumen depreciation, energy savings*

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R.M.L. Chamari

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List of Abbreviations

Abbreviation	Description
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
CCT	Correlated Colour Temperature
CRI	Colour Rendering Index
IES	Illumination Engineering Society
kVA	Kilovolt-ampere
kW	Kilowatt
kWh	Kilowatt-hour
LED	Light Emitting Diode
LEED	Leadership in Energy and Environmental Design
LLMF	Lamp Lumen Maintenance Factor
LMF	Luminaire Maintenance Factor
LPD	Lighting Power Density
MEP	Minimum Energy Performance
MF	Maintenance Factor
PF	Power Factor
RMF	Room Maintenance Factor
UF	Utilization Factor
USGBC	U.S. Green Building Council

CHAPTER 1

1 INTRODUCTION

Lighting plays a major role in maintaining comfort and productivity of the occupants of any type of environment. On average electric lighting accounts for around 35% of commercial building energy consumption [1]. Therefore, using energy efficient lighting is very important. After the phasing out of incandescent lights from large commercial building lighting applications, fluorescent and compact fluorescent lights were the dominant artificial light source in the recent years. Compared to fluorescent lights with magnetic ballast, T8 and T5 lights with electronic ballasts were highly efficient. And today, commercial high-power Light Emitting Diodes (LEDs) have become more competent to challenge traditional light sources with their high luminous efficacy over 100 lm/W and longer lifetime exceeding 50000h of useful life [2].

In 2014, the Nobel Prize in Physics was won for "the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources" [3]. Nowadays LED based luminaires are extensively being used as the total lighting solution in many homes, buildings and streets. There are many benefits of LEDs including but not limited to, easiness in adjusting luminous flux, availability of different and tuneable Correlated Colour Temperatures (CCT), flexibility of achieving many light colours, easiness in controlling the light intensity distribution, electronic control of the power supply, higher energy efficiency, long operating life and increased affordability due to decreasing costs over the years [4].

1.1 Types of LED light sources used in buildings

Normally, a light fixture is a lamp mounted within fitting with reflectors or diffusers. LED luminaires are also available in this form, especially as a retrofitting for an available light fixture which has used fluorescent or compact fluorescent lamps.

There are directional and non-directional LED lamps with many different shapes with lamp caps of B15, B22, E14, E27, E40, GU10 and G9. Also, there are double-capped

LED lamps to replace fluorescent tubes including G5 and G13 caps. These lamps are mostly used as a retrofit for less efficient traditional lamps.

Figure 1.1 : LED lamps (Source: www.eiko.com)

But, not only these LED light sources are available in "lamps" type as in other light sources, LEDs are integrated into the light fixture itself, and these are called "LED luminaires".

The LED luminaire is a complete unit including the light engine, optics, thermal management components and driver circuit. These LED luminaires are available in many different sizes and wattages in the range of 1W~400W depending on the application.

Figure 1.2: LED luminaires (Source: www.eiko.com)

Although there is no universal classification for LED light sources used in commercial buildings, one such useful classification was derived from the "Energy Rating Australia Draft Minimum Energy Performance Standards for LED Lighting" as below.

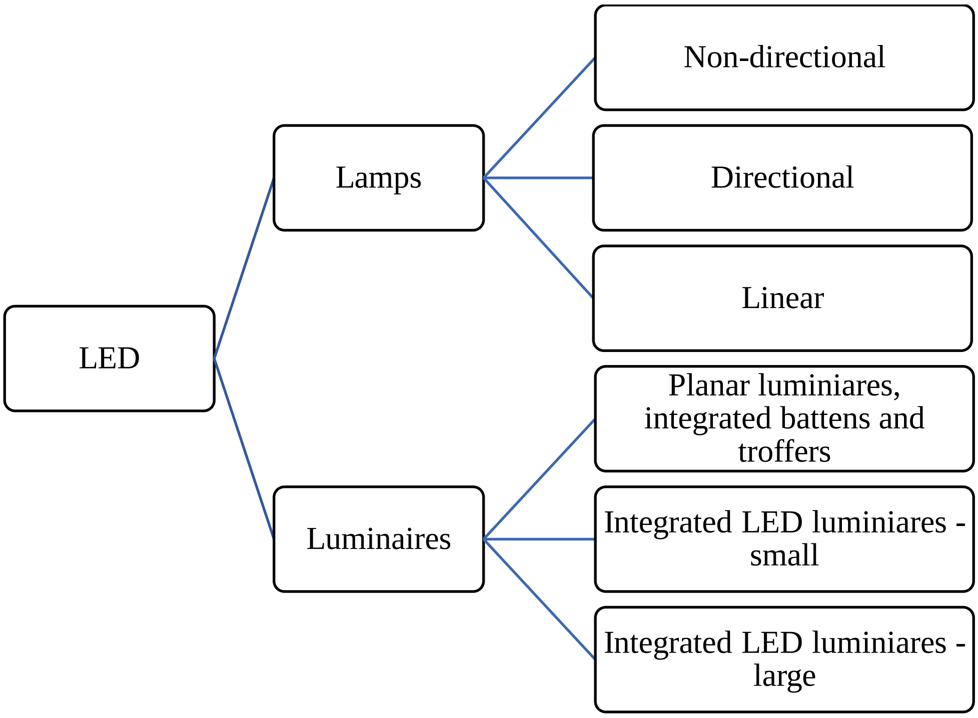


Figure 1.3 : Classification of LEDs according to "Energy Rating Australia Draft Minimum Energy Performance Standards for LED Lighting"

Non-directional LED lamps: Lamps with LED light sources of all shapes with lamp caps B15, B22, E14, E27, E40, GU10, G9 and ELV lamp bi-pin caps G4, that emit ≥ 100 lm [5].

Directional LED lamps: Lamps with LED light sources of all shapes with lamp caps B15, B22, E14, E27, E40, GU10, G9 and R7, and ELV lamp bipin caps GU5.3, GX5.3, G6.35, GX53, that emit ≥ 100 lm [5].

Linear LED lamps: Linear LED lamps double-capped LED lamps including G5 and G13 caps, intended for replacing fluorescent lamps (as defined in IEC 60081) with the same caps (as defined in IEC 60081) or caps specific for double-capped linear LED lamps with a nominal length of 550 mm to 1500 mm [5].

Planar Luminaires, integrated battens & Troffers: Integrated LED fixtures (including panel form) intended as an alternative to tubular fluorescent based general purpose troffer/recessed luminaires and batten/fixed general-purpose luminaires, suspended or surface mount [5].

Integrated LED Luminaires (small): Integrated LED luminaires with a luminous flux of ≥ 100 lm and < 2,500 lm. Integrated includes a luminaire with remote control gear [5].

Integrated LED Luminaires (large): Integrated LED luminaires with a luminous flux of ≥ 2,500 lm and < 50,000 lm. Includes integrated LED fixtures intended as an alternative to general purpose industrial style high bay, low bay and indoor area lighting luminaires [5].

1.2 Performance standards for LED luminaires

Three new standards dedicated to LED lighting were identified.

1. IESNA LM-79: IESNA Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting

LM-79 is used to measures the electrical and photometric properties of LED products including luminous flux, electrical power, efficiency, chromaticity as well as the diffusion of luminous intensity.

2. IESNA LM-80-08: IESNA Approved Method for Measuring Lumen Maintenance of LED Lighting Sources

LM-80 is used to measures the maintenance of the luminous flux for a group of LEDs at various operating temperatures. Testing over the course of a minimum of 6,000 hours is recommended. Measurements are taken at 1,000-hour intervals.

3. IESNA TM-21-11: Projecting Long Term Lumen Maintenance of LED Light Sources

TM-21 provides guidelines to allow LM-80 tests to extrapolate the lifetime beyond what is measured by LM-80. It is allowed to extrapolate the lifespan up to six times the number of test hours. If the LEDs are only tested for 6 000 hours in a laboratory, a lifespan greater than 36,000 hours based on the L70 lifespan is not to be expressed by a manufacturer.

1.3 Lighting design aspects

When designing and implementing a lighting system for a building, there are number of factors that need to be considered. Traditionally, maintaining a sufficient illumination level, distribution of brightness harmoniously, avoiding discomfort glare, avoidance of reflections, appropriate light colour and colour rendering were the key parameters. However, with the technological advancement, more requirements came into play such as mood lighting, personal control and also lighting as an interior design element. Also, requirements like energy efficiency, daylight integration and lighting control systems became a must in recent years due to the increased attention on energy crisis. In this era, sophisticated lighting simulation software have made it possible for the designer to work with many complex requirements by integrating different luminaire data provided by manufacturers.

1.4 Problem Statement

LED lighting is a blooming field with massive financial and environmental benefits. Thus, the question “are we gaining all these benefits in current LED lighting systems in Sri Lanka?” remains due to several reasons.

1. Evaluating performance of LED products is complex

It is difficult to determine the quality of LED products. Different manufacturers use various technical terms to define their products ' quality, making it difficult to compare them. In fact, a product's technological design can make a tremendous difference in efficiency. Even if two luminaires are based on exactly the same LEDs, due to design choices made, their quality may be different. The effectiveness of the heat management, the driver and the optics can increase or decrease the efficacy of the total LED based luminaire.

2. Buying decision is based on initial cost, not the total cost for lifetime

In any project, initial cost plays a major role in the buying decision. However powerful the lighting design is, when it comes to the decision of purchasing luminaires, most of the design aspects are compromised for lower prices. Sometimes, lower initial cost does not necessarily mean the lowest total cost for lifetime since there are other cost components attached to a lighting system in its lifetime such as energy cost and maintenance cost. This is critical when used LED luminaires, since they are chosen for a project to last for around twenty to thirty years.

3. No minimum energy performance (MEP) requirements for importing LED luminaires to Sri Lanka

Currently there are no restrictions on the quality of LED luminaires being imported to Sri Lanka. Therefore, LED luminaires can be purchased for lower prices with lower performance. Since they have the price advantage, and sometimes being any “LED” means energy efficient, they are easily entered into the buildings.

4. LED market is flooded with low quality LED luminaires for lower prices

Manufacturers and contractors who prioritize cost reductions over the reliability of the lighting system has led low-quality LED fixtures to penetrate into the Sri Lankan lighting market. Absence of proper guideline or rating scheme for LED fixtures has created ambiguity among customers and lighting designers when purchasing LED luminaires.

5. No national guideline for choosing the right LED luminaire

In Sri Lanka, Code of practice for Energy Efficient Buildings is currently used as the guideline for achieving the energy efficiency in lighting. Final version as at today (December 2019) is the code released in 2008 sets energy efficiency measures such as lighting power density, efficacy and maximum ballast losses for fluorescent, compact fluorescent, incandescent and high intensity discharge type lamps only.

6. Standard warranty of two years for a luminaire that is designed to last around twenty years

Despite the fact that manufacturers specify long lifetime for LED in the range of thirty thousand to hundred thousand operating hours, standard warranty given by most of the suppliers are in the range of two to five years. Also, contractors in many projects are liable for defects for only one or two years. Therefore, the performance after this warranty period is not guaranteed.

7. In many buildings light levels are not properly monitored.

Light levels should be monitored to ensure that the available light levels are adequate for the purpose they are designed for. But this practice is very poorly implemented in most of the buildings. Even if the light levels are measured, it is done in the initial stage only and not measured continuously throughout the building usage. Other than soiling and ageing of lamps, luminaires and room LEDs inherently diminishes its light output over time. The normal practice is measuring the initial light levels and comparing them with the design light levels. If these two matches, it is considered as adequate. Therefore, when the light levels will further reduce over time it will not provide adequate amount of light during the whole period of time.

8. Neglecting the importance of LED maintenance factors

Light output of LED luminaires is continuously reducing over time, until the end of lifetime is reached. To compensate for this and other reasons like soiling and ageing of lamps, luminaires and room, initial number of luminaires should be increased in the design. Therefore, initially light levels should be higher than what is required and the design light level should be maintained even at the luminaire's minimum light output during the lifetime of the lighting system.

According to the building code of Sri Lanka Sustainable Energy Authority (SLSEA), in the submission procedure the engineer or architect responsible for the lighting installation shall provide a complete set of plans to the building owner, depicting lighting devices, also to be accompanied by the following information.

a) The standard and design-maintained illuminance for all the interior spaces

b) The specifications and numbers of each type of lighting device
c) The total wattage of each type of lighting device including nominal rating and control gear losses.
d) The installed lighting load for interior and exterior spaces.

There is no submission regarding the maintenance factors used in the design or the light level maintenance throughout the lifetime of the installation.

Due to these reasons, it is inevitable that the chosen lighting systems in a building will not be the most beneficial solution, and even if it was, it will not perform at its maximum potential.

In this research, general criteria for selecting the most beneficial LED luminaire system for a building is proposed considering its total lifetime costs and performance. These guidelines will be beneficial for anyone who is interested in the field of lighting engineering. React - a JavaScript library for building user interfaces was used to create an evaluation tool to compare different LED luminaires simultaneously and the results are presented graphically in a meaningful manner.

1.5 Objective

The objective of this research is to develop criteria that can be used for a comprehensive lighting design and evaluation of different LED luminaires simultaneously. These criteria should take design lifetime, performance of the LED luminaire throughout the design lifetime, performance of the LED luminaire under actual operating conditions, building code compliance and total cost for lifetime into consideration.

CHAPTER 2

2 LITERATURE REVIEW

2.1 Transition towards LED lighting in Sri Lanka

There are very few researches carried out in Sri Lanka with regards to LED lighting. Most of the available ones are economical comparisons between traditional light sources and LED light sources. One of those researches were focused on finding the “economic feasibility of replacing conventional lighting devices with LEDs in Sri Lanka”. In that research, a sample of LED, CFL and conventional bulbs were used to analyse the active power requirement to light up the same building separately, while maintaining the same lighting level. Modelling was done with DIALux software. Apparent power was compared against different power factors, to find out which type of lighting device draws more power to emit the same light level. Findings had shown that energy saving by LEDs is 32% compared with CFLs, and 174% compared with incandescent at this “use” phase [6].

Another research was focused on “evaluation of effectiveness of LED Lighting in Buildings”. The study focused on a design that replaces existing fluorescent lamps (most commonly “T8” linear lamps) with LED products in a commercial building. Light levels were not in the adequate levels with the existing fluorescent lighting system and the LED lamps were installed to upgrade the light levels to standard levels. A cost analysis was done for one lamp from each type for a period of 60 months. The key benefit of LED technology for general lighting application was identified as the reduced maintenance cost due to their long-life [7] .

A research on “Analysis on Energy Efficiency and Optimality of LED and Photovoltaic Based Street Lighting System” had found the equivalent LED light fittings to replace existing incandescent, fluorescent, CFL, mercury vapour and sodium vapour lamps in Sri Lankan street lights. It was realized through this study that it is possible to implement efficient street lighting system by combining automatic lamp controls with LED lamps for existing street lamps except CFL. Except CFL, LED replacement assessed in this option shows significant energy and maintenance savings potential, achieving 40% to 80% savings compared to the existing street lamps [8].

However, none of the researches were into more technical details about the LED lamp or luminaire configuration they have used. Since these research findings were based on a comparison between one traditional light source and one LED light source, and there exist many differences between the LED lamps and luminaires available in the market, the effect of which LED lamp or luminaire was selected for the study was not highlighted. In fact, there might be other LED lamps or luminaires which could yield better or worse results and that could directly affect the cost benefit analysis. There were no clear criteria based on which these LEDs were selected.

By studying the above and many other researches, it was understood that a set of guidelines and general criteria for achieving the best LED luminaire for a given application is needed for Sri Lanka, especially with the rising interest and demand for LED luminaires.

2.2 Worldwide standards for efficient lighting

Energy efficiency in buildings is considered as a matter of immediate attention due to the scarce in natural resources, greenhouse gas emissions and climate change followed. Studies show that the building sector accounts for over 40 percent of world energy requirements and a large percentage of the present energy consumption and carbon dioxide generation could be saved by applying certification standard [9]. Since lighting accounts for a large portion of the total energy share in a building, countries all over the world are setting limits to which electricity can be used for lighting. These are briefly discussed below.

2.2.1 ANSI/ASHRAE/IESNA Standard 90.1

Standard 90.1 provides minimum requirements for the energy-efficient design of buildings and building systems. The Standard specifies reasonable design practices and technologies that minimize energy consumption without sacrificing either the comfort or productivity of the occupants. This standard covers the design of the building envelope, lighting systems, Heating Ventilation and Airconditioning (HVAC) systems, and other energy-using equipment. In this standard, following steps must be followed to determine the allowed lighting power for a building.

1. Determine the appropriate building type and the corresponding Lighting Power Density (LPD) allowance.
2. Determine the gross lighted floor area of the building area type.
3. Multiply the gross lighted floor areas of the building area with LPD.
4. The interior lighting power allowance for the building is the sum of the lighting power allowances of all building area types.

In addition to being used for code compliance, Standard 90.1 is often used as a baseline for energy efficient and green building programs. An example of such a program is the U. S. Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) program [1].

Table 2.1 : Lighting Power Density Allowances Using the Building Area Method according to Table 9.5.1 of ANSI/ASHRAE/IESNA Standard 90.1

Building Area Type	**LPD (W/m^2)**						
	1999	**2004**	**2007**	**2010**	**2013**	**2016**	**2019**
Office	13.99	10.76	10.76	9.69	8.83	8.50	6.89
School/University	16.15	12.92	12.92	10.66	9.36	8.72	7.75
Warehouse	12.92	8.61	8.61	7.10	7.10	5.17	4.84
Manufacturing Facility	23.68	13.99	13.99	11.95	12.59	9.69	8.83

2.2.2 Environmental Protection Agency (EPA) EnergyStar™

U.S. Environmental Protection Agency (EPA) and Department of Energy (DOE) had jointly developed the ENERGY STAR program as a way to encourage energy efficiency. This has led to ENERGY STAR appliances, an ENERGY STAR rating for residential housing and the ENERGY STAR commercial building rating.

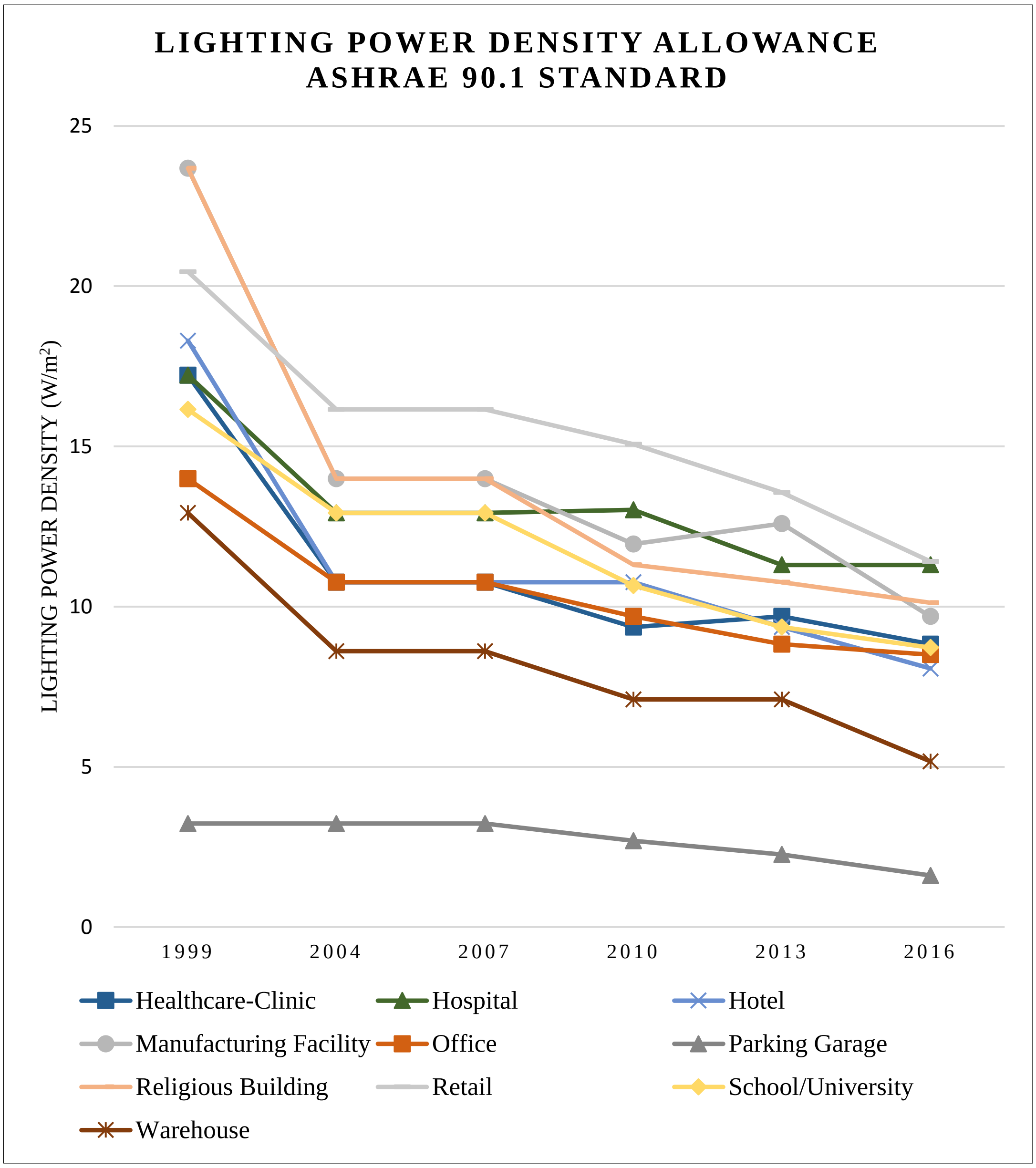


Figure 2.1 : Evolution of LPD allowance according to ASHRAE 90.1 Standard

The ENERGY STAR product label is generally reserved for residential lighting products. However, there are some commercial projects where ENERGY STAR products may be appropriate. Commercial spaces that use residential type fixtures, such as hotels, nursing homes and apartment buildings would benefit from using ENERGY STAR certified lighting products. However, ENERGY STAR lighting products are not specified for open offices, warehouses and other large commercial or industrial spaces where commercial LED luminaires are preferred, since these types of luminaires are not labelled by the ENERGY STAR program [10].

2.2.3 The E3 Program

The Equipment Energy Efficiency (E3) program is a collaboration program where Australian Government, states and territories and the New Zealand Government presents an integrated program on energy efficiency standards and energy labelling for equipment and appliances. E3 has introduced energy rating labelling, setting minimum MEPS and education and training. The MEPS specify minimum performance levels for lighting efficacy and a number of other performance parameters important to ensure LED lighting provides an effective and efficient alternative to other less efficient lighting technologies [11].

Draft Minimum Energy Performance Standards for LED Lighting – V5 28 July 2016 sets MEPs for both LED lamps and LED integrated luminaires.

Table 2.2 : Draft Minimum Energy Performance Standards for LED Lighting by Energy Rating Australia

LED category	Efficacy	Colour Rendering	Lumen maintenance	Rated Life Declaration	Power Factor
Non-directional LED lamps	≥ 65 lm/W ≥ 85 lm/W (2020) ≥100 lm/W (2023)	Ra ≥ 80	Lumen maintenance @ 6000 hrs Lx,6k ≥ 86.7% (based on L70B50 ≥ 15,000h)	Minimum lifetime of 15,000 hours	< 25W: PF > 0.50 ≥ 25W: PF > 0.90

Directional LED lamps	≥ 65 lm/W ≥ 85 lm/W (2020) ≥100 lm/W (2023)	Ra ≥ 80	Lumen maintenance @ 6000 hrs Lx,6k ≥ 86.7% (based on L70B50 ≥ 15,000h)	Minimum lifetime of 15,000 hours	< 25W: PF > 0.50 ≥ 25W: PF > 0.90
Linear LED lamps	≥ 100 lm/W ≥ 110 lm/W (2020) ≥ 120 lm/W (2023)	Ra ≥ 80	Lumen maintenance @ 6,000h Lx,6k ≥ 91.8% (based on L70B50 ≥ 25,000h)	Minimum lifetime of 25,000 hours	PF > 0.90
Integrated LED Luminaires (small) (luminous flux of ≥ 100 lm and < 2,500 lm)	≥ 65 lm/W ≥ 85 lm/W (2020) ≥100 lm/W (2023)	Ra ≥ 80	Lumen maintenance @ 6,000h Lx,6k ≥ 93.1% (based on L70B50 ≥ 30,000h)	Minimum lifetime of 30,000 hours	PF > 0.90
Integrated LED	≥ 90 lm/W ≥ 110 lm/W	Ra ≥ 80	Lumen maintenance	Minimum lifetime of	PF > 0.90

Luminaires (large) (luminous flux of ≥ 2,500 lm and < 50,000 lm)	(2020) ≥ 120 lm/W (2023)		@ 6,000h (Lx,6k) ≥ 95.4% of initial (based on L70B50 ≥ 45,000h)	45,000 hours	
Planar Luminaires, integrated battens & Troffers	≥ 90 lm/W ≥ 110 lm/W (2020) ≥ 120 lm/W (2023)	Ra ≥ 80	Lumen maintenance @ 6,000h (Lx,6k) ≥ 95.4% of initial (based on L70B50 ≥ 45,000h)	Minimum lifetime of 45,000 hours	PF > 0.90

2.2.4 Code of practice for Energy Efficiency Buildings in Sri Lanka - 2008, Sri Lanka Sustainable Energy Authority (SLSEA)

Code of practice for Energy Efficiency Buildings in Sri Lanka has introduced criteria and minimum standards for energy efficiency in design and/or retrofits in commercial buildings. It also provides criteria for determining compliance and to encourage energy efficiency designs exceeding minimum standards [12] .This code is referred by many design engineers for lighting design practices.

This code has set the maximum allowable loads for building lighting systems as well as lower limits for the acceptable efficiencies for commonly used lighting components (lamps and ballasts). But these limits are imposed on incandescent, high intensity discharge lamps, fluorescent and compact fluorescent lamps only. However, next building code will set the minimum performance of LED lamps as well.

Building code provides upper limits to the LPD based on the building category. By examining these values, it can be seen that these values are based on ASHRAE 90.1 2008 version. However, the code recommends fluorescent and CFL for normal lighting applications and high-pressure sodium vapour or metal halide lamps for high bay applications and these will soon be updated in a newer version.

Following regulatory instruments were initiated by the SLSEA.

Table 2.3 : Regulatory instruments initiated by the SLSEA regarding lighting efficiency

Description	Standard Number	Regulation	Progress
Compact Fluorescent Lamps (CFLs)	SLS 1225:2002	1611/10 of 22nd July 2009	The revised Standard on Energy Labelling for CFLs has been published.
Ballasts	SLS 1200:2012	1971/12 of 15th June 2016	Mandatory energy label available.
Linear Fluorescent Lamps	SLS 1625: 2013	1971/12 of 15th June 2016	Voluntary energy label was developed and implemented for LED lamps. Draft regulations to implement the scheme on a mandatory basis is under formulation.
LED	SLS 1530: 2016	N/A	Minimum Energy Performance Standards are available

2.3 Lifetime of LED

Although many manufacturers claim that their LED lighting will last 100,000 hours, a group of researchers in Lighting Research Center has found out that it was not true under realistic conditions such as, when integrated with optics and housing and installed in a recessed luminaire in insulated plenums. Even though a single, bare LED might last that long, when it is integrated into a lighting system, LED life could be far less. When integrated with optics and housing and installed in a recessed luminaire in insulated plenums it becomes very complicated to estimate the lifetime of LED [13].

The recommended method to express the lifetime of an LED system is defined as the time to reach 70% lumen maintenance in hours as shown in Figure 2.2 : Lumen depreciation profile and end of useful life criterion (L70) for LEDs. The justification for this value of 70% as found by a research is as below. For general lighting applications, 70% lumen maintenance (or 30% reduction of light levels) is considered as the threshold for a human to detect the gradual light output in a space and the 70% value considered acceptable value by majority of occupants [14]. However, by studying the manufacturers' datasheets, other than he L70 and L50 values, some manufacturers have provided figures like L80 and L90 as well.

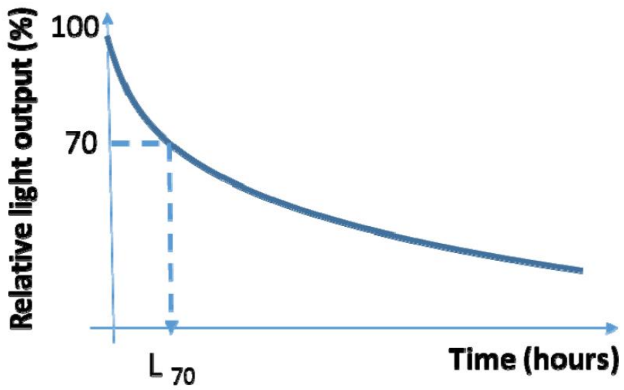


Figure 2.2 : Lumen depreciation profile and end of useful life criterion (L70) for LEDs

Lumen depreciation for LED packages is also affected by operating conditions and varies substantially between different products. The expected lumen maintenance for a single type of LED package can be very different based on the junction temperature, which is affected by the drive current, ambient temperature, and thermal performance of the lamp or luminaire in which the package is used. Measured and projected lumen maintenance of one type of LED package at three different case temperatures is shown in Figure 2.3 : Measured and projected lumen maintenance of one type of LED package at three different case temperatures. (Source: Lumen Maintenance and Light Loss Factors: Consequences of Current Design Practices for LEDs). Even though the lifetime of LED source can be very long, lifetime of the LED driver can be shorter, and that will lead to a shorter lifetime of the complete system [2]. Also, when the heat dissipation is poorly designed, heat cannot be properly removed and that could significantly reduce the life of LEDs [15].

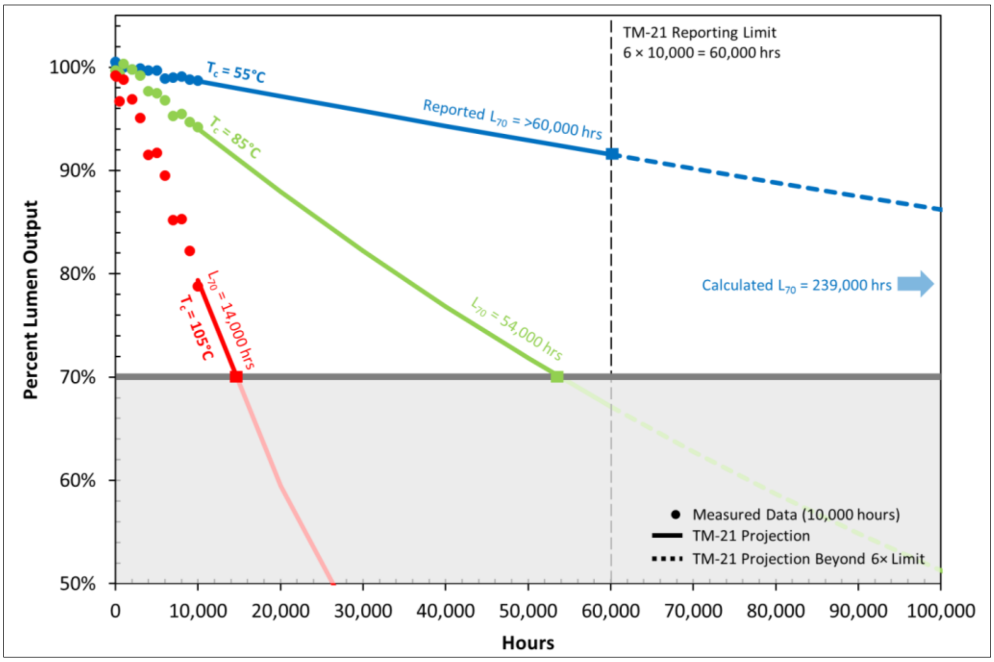


Figure 2.3 : Measured and projected lumen maintenance of one type of LED package at three different case temperatures. (Source: Lumen Maintenance and Light Loss Factors: Consequences of Current Design Practices for LEDs)

2.4 Lighting calculations

When designing a lighting system, major design consideration is to provide an appropriate quantity of light for a given task, without being too high or low. Lighting calculations are done to predict performance of the lighting system and to make sure the design meets performance recommendations. The design light levels are typically chosen from an IES publication such as the IES Lighting Handbook or a national guideline. For this, simple and advanced calculations are performed based on the requirement.

2.4.1 Lumen Method Calculations

The lumen method is a hand calculation method for predicting the performance of a general lighting system providing reasonably uniform illumination.

The method follows four main steps.

1. For a given space, determine the room cavity ratio (RCR) or room index (RI) and reflectance of the room surfaces.
2. Choose luminaire. From the photometric reports, determine the CU of the lighting system based on RCR/RI and reflectance.
3. Determine the applicable maintenance factors.
4. Solve the lumen method equation for either average illumination level for a given number of luminaires, or for the number of luminaires to meet a specific illumination level.

However, this method can be used to calculate the average illuminance in a certain working plane and cannot be used to predict specific illumination levels or the variance of light levels in the given space.

2.4.2 Radiosity and Ray Tracing Calculations

Computer calculations for predicting lighting system performance are significantly more accurate than the lumen method. They also can produce impressive reports and renderings. In general, computer methods predict the illumination at specific points in the space ("point-by-point" illumination) permitting a detailed evaluation of lighting performance [16]. Input to these programs consists of a complete description of the space in three dimensions complete with furniture, ceilings and walls. Each luminaire's characteristic photometric report is part of the program input. They are plain text files with the IES file extension that contain data on light for architectural programs that can simulate light. Some professional Lighting simulations software used widely in the industry are DIALux, Relux and AGi32.

2.5 LED Maintenance Factors

All lighting systems decline in lumen output over time due to reductions in lamp emissions and changing surface properties such as lamp, luminaire and room. This reduction in light output is typically accounted for by applying a light loss factor (LLF) during the design process. LLF is a multiplier that is used to predict maintained illuminance based on the initial properties of a lighting system. This value is typically less than 1.0 and therefore, the initial light level will be above the recommended target value. But as time progresses, the light level will decline and sometimes below the recommended levels. LLF is commonly calculated as the ratio of mean to initial lumens, where mean lumens are defined as the output at a certain percentage of rated life, based on the lumen depreciation curve for a specific product [17].

CHAPTER 3

3 METHODOLOGY

The methodology which was carried out during the study is illustrated below.

3.1 Current LED luminaire-based lighting practices

By analysing lighting designs done for various projects in the industry and conducting interviews with electrical design engineers from consulting firms, how the various parameters of LED luminaires are incorporated in the lighting design calculations was studied. In order to identify the expectation level of technical details, light fitting specifications and bill of quantities prepared for different types of projects were studied. Four common commercial building spaces were used for the study namely, office, educational institutes, factory and warehouse.

3.2 Collecting electrical and photometric data of LED luminaires

Electrical and photometric data of LED luminaires available in Sri Lankan market were obtained from manufacturers' websites and through suppliers. It was observed that large number of LED suppliers are present in the market with a wide variety of LED luminaires with different countries of origin as well. After studying the LED luminaire datasheets, it was clear that some of the fixtures had high technical details while some of them were lacking the basic technical detail such as lifetime.

3.3 Obtaining the market prices

Market prices for LED luminaires were obtained from light fitting suppliers. A large difference in prices between LED luminaires was observed. Efficacy, CRI and power factor remains closely equal but when the lifetime of the LED luminaire was higher, the luminaires were more expensive. Also, luminaires with European origin were very expensive compared to the luminaires with Chinese origin.

3.4 Shortcomings of current LED luminaire-based lighting practices

Lighting design guidelines, standards, building codes in other countries, LED luminaire datasheets from different manufacturers, whitepapers published by different manufacturers and research papers based on LED technology were studied thoroughly to identify the shortcomings in existing lighting practices.

3.5 Finding the minimum efficacy requirement for building spaces

Since the main goal of LED lighting is achieving more energy efficiency, the most important parameter of a luminaire is the efficacy. Therefore, a relationship between the recommended LPD values for building space and efficacy of the luminaire was derived to identify the lowest acceptable efficacy values for a luminaire. Based on this relationship, minimum efficacy required for the selected four building types selected were obtained.

3.6 Lighting calculations

Proper lighting calculation is key to a good design. In this study a comprehensive calculation method was used to achieve the most suitable lighting system for a given application. Different LED luminaires had to be compared simultaneously. Each LED luminaire with different characteristics was considered as a separate scenario. The flexibility, easiness and ability to represent the results graphically was reduced when using spreadsheet calculations for many scenarios. Therefore, a software tool was developed using React js to perform the lighting calculations under different scenarios and graphically represent the results.

3.6.1 Determine the number of luminaires required

Determining the number of luminaires required to achieve the maintained lux levels to suit the application is the main goal in a lighting design. This is done by hand calculations using the Lumen method in a spreadsheet format for the applications that requires uniform light distribution in a closely rectangular shape. For more complex building shapes and non-uniform light distributions, software simulations are carried out.

3.6.1.1 Zonal Cavity Method (Lumen Method)

The Zonal Cavity Method (Lumen Method) is used for calculating average illuminance levels for indoor areas, unless the light distribution is radically asymmetric. The space between the ceiling and the fixtures, if they are suspended, is defined as the "ceiling cavity"; the space between the work plane and the floor, the "floor cavity"; and the space between the fixtures and the work plane, the "room cavity." Once the concept of these cavities is understood, it is possible to calculate numerical relationships called "cavity ratios," which can be used to determine the effective reflectance of the ceiling and floor cavities and then to find the coefficient of utilization.

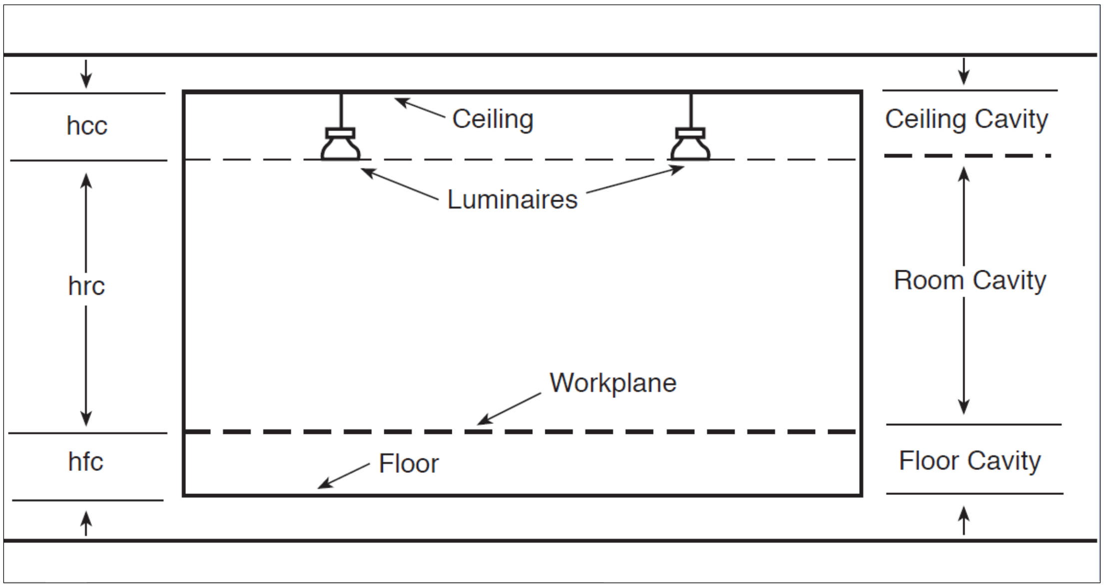


Figure 3.1 : Room elements of Zonal Cavity Method (Lumen Method)

Following equations are used as the basis for Lumen Method calculations.

Average Illuminance (E) is given by,

$$E = \frac{F \times n \times N \times UF \times MF}{A} \qquad (3.1)$$

F = initial bare lamp luminous flux (lumens)

n = number of lamps per luminaire

N = number of luminaires

UF = utilisation factor

MF = maintenance factor

A = area of the surface (m^2)

Room Index (K) is given by,

$$K = \frac{L \times W}{(L+W) \times h_m} \tag{3.2}$$

L = length of the room

W = width of the room

h_m = height of luminaire above horizontal reference plane

Maintenance factor (MF) is given by,

$$MF = LLMF \times LSF \times LMF \times RSMF \tag{3.3}$$

LLMF = Lamp lumen maintenance factor

LSF - Lamp survival factor

LMF - Luminaire maintenance factor

RSMF - Room surface maintenance factor

Required number of luminaires (N) is given by,

$$N = \frac{E \times A}{F \times n \times UF \times MF} \tag{3.4}$$

Spacing to height ratio (SHR) is given by,

$$SHR = \frac{1}{H_m}\sqrt{\frac{A}{N}} \tag{3.5}$$

H_m = mounting height

A = total floor area

N = number of luminaires

3.6.1.2 Utilization Factor (UF)

The coefficient of utilization (CU) is a measure of the percentage of lumens incident on the work plane to the total emitted lumens from the lamps in the luminaire. The CU value takes into account the room geometry, surface reflectance, and efficiency and distribution of the luminaire. CU table is provided by the manufacturer along with the luminaire datasheet. If CU table is not given in the datasheet, it can be generated from the. ies luminaire file using a software. In this study, Photometric Toolbox-2.7 software was used to generate the CU table from the. ies luminaire file. To find the UF from the CU table, ceiling, wall and floor cavities should be calculated from below formula.

$$\text{Cavity Ratio} = \frac{2.5 \times \text{height of the cavity} \times \text{cavity perimeter}}{\text{area of cavity base}} \qquad (3.6)$$

Table 3.1 : Utilization factors according to CEN/TR 15193-2:2017

Upward flux fraction (UFF)	Room index k									
	0,6	0,8	1	1,25	1,5	2	2,5	3	4	5
10 % (direct)	0,45	0,52	0,56	0,62	0,64	0,69	0,72	0,76	0,79	0,79
30 % (dir./ind.)	0,39	0,44	0,48	0,51	0,54	0,57	0,60	0,62	0,64	0,67
70 % (ind./dir.)	0,26	0,31	0,36	0,41	0,45	0,51	0,56	0,57	0,64	0,67
90 % (indirect)	0,19	0,24	0,28	0,33	0,36	0,43	0,48	0,52	0,57	0,62
Reference case (UFF=0 %) $F_{U,e}$	0,50	0,61	0,69	0,78	0,84	0,90	0,95	0,99	1,03	1,05
NOTE Intermediate values of the room index can be interpolated.										

For the determination of the values given in the table the following typical reflection coefficients were applied: ceiling: 70 %, walls: 50 %, floor: 20 %.

3.6.1.3 Lamp Lumen Maintenance Factor (LLMF)

In this study, three methods were used to derive LLMF.

Method 1: Using the end of life light percentage and design lifetime to derive LLMF.

Sometimes the design lifetime of the lighting system may be smaller than the time it takes for the LED to reduce its light output to 70%. This will be true for high performance LED luminaires which are designed to maintain more than 90% light output even after 100,000 hrs of operation as shown in Table 3.2 : Lumen Maintenance Factors for Cree Edge™ high output High Bay.

In this scenario, LLMF was derived using the equation 3.7 below.

$$\text{LLMF} = 1 - \frac{\text{Design lifetime}}{\text{Luminaire lifetime}} \times (1 - \text{LLMF@rated lifetime}) \qquad (3.7)$$

For an LED luminaire with 0.92 LLMF @ 100,000Hrs, LLMF @ 50,000Hrs is 0.96.

Table 3.2 : Lumen Maintenance Factors for Cree Edge™ high output High Bay

Cree Edge™ High Output Ambient Adjusted Lumen Maintenance[1]					
Ambient	Initial LMF	25K hr Projected[2] LMF	50K hr Projected[2] LMF	75K hr Calculated[3] LMF	100K hr Calculated[3] LMF
5°C (41°F)	1.04	1.01	0.99	0.98	0.96
10°C (50°F)	1.03	1.00	0.98	0.97	0.95
15°C (59°F)	1.02	0.99	0.97	0.96	0.94
20°C (68°F)	1.01	0.98	0.96	0.95	0.93
25°C (77°F)	1.00	0.97	0.95	0.94	0.92
30°C (86°F)	0.99	0.96	0.94	0.93	0.91
35°C (95°F)	0.98	0.95	0.93	0.92	0.90
40°C (104°F)	0.97	0.94	0.92	0.91	0.89
45°C (113°F)	0.96	0.93	0.91	0.90	0.88

Above two scenarios are illustrated in Figure 3.2 : LLMF values @ 50,000Hrs for two LEDs

Method 2: Using the end of life light percentage to derive the LLMF.

Most of the time, design lifetime of the lighting system of a building is larger than the lifetime of an LED luminaire. Since the lifetime of LED is defined as the time when its initial light output reaches 70%, LLMF can be considered as 0.7 for all luminaires in this scenario.

Method 3: Using the mean lumen output to initial lume n output ratio to derive LLMF.

$$\text{LLMF} = \frac{\text{Mean lumen output}}{\text{Initial lumen output}}$$

Here**,** the mean light output stands for lumen output at the time corresponding to 40% of the design lifetime.

For an installation with design lifetime of 100,000Hrs, time corresponding to mean light output is 40,000Hrs. Therefore, assuming that the depreciation is linear, LLMF of LED will be 0.76 and LED 2 will be 0.968.

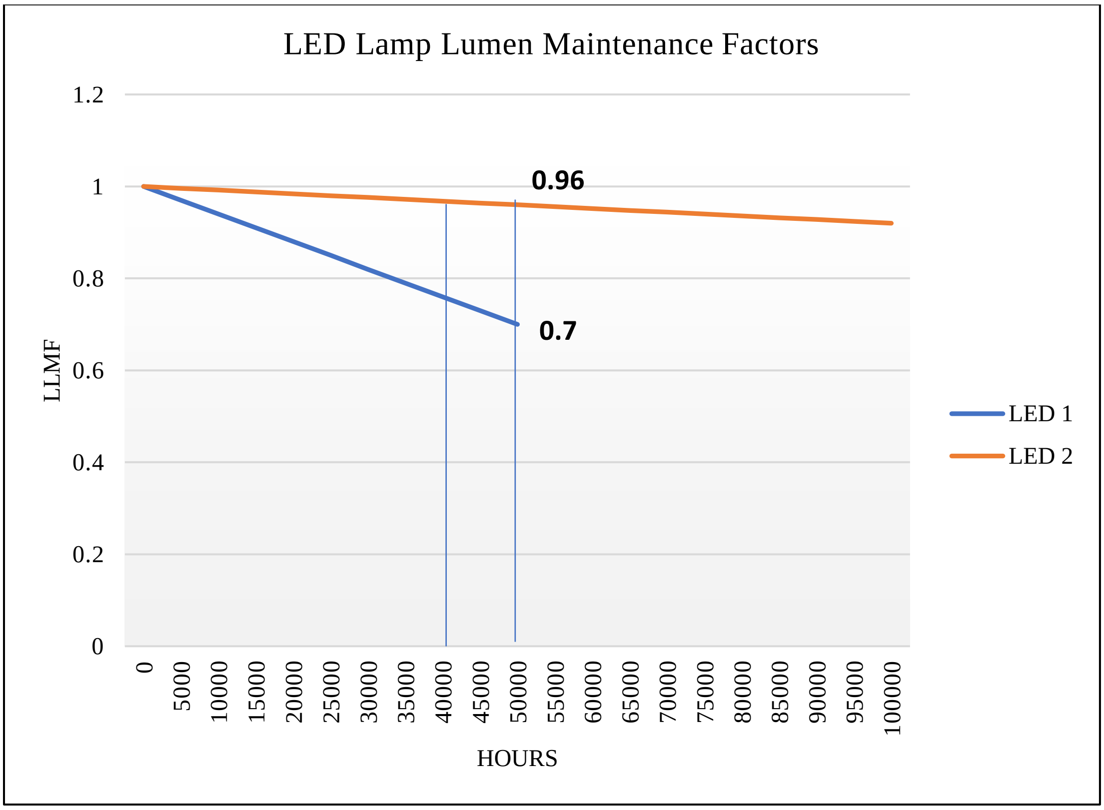


Figure 3.2 : LLMF values @ 50,000Hrs for two LEDs

3.6.1.4 Room Surface Maintenance Factor (RSMF)

RSMF is chosen from BS EN 15193 according to the combination of ceiling/wall/floor reflectance, room cleaning interval and environment conditions. Here, direct flux distribution was chosen since the application of interest was commercial buildings.

Table 3.3 : Luminaire classes according to CEN/TR 15193-2:2017

Class	Description
A	Bare lamp batten
B	Open top reflector (ventilated self-cleaning)
C	Closed top housing (unventilated)
D	Enclosed (IP2X)
E	Dustproof (IP5X)
F	Indirect uplighter
G	Air handling and forced ventilated

Table 3.4 : Environmental conditions according to CEN/TR 15193-2:2017

Environment	Typical Locations
Very Clean (VC)	Clean rooms, semiconductor plants, hospital clinical areas, computer centres
Clean (C)	Offices, schools, hospital wards
Normal (N)	Shops, laboratories, restaurants, warehouses, assembly areas, workshops
Dirty (D)	Steelworks, chemical works, foundries, welding, polishing, woodwork

Table 3.5 : LMF values for indoor use according to CEN/TR 15193-2:2017

Elapsed time between cleanings in years	0,5				1,0				1,5				2,0				2,5				3,0			
Luminaire type	Environment																							
	VC	C	N	D	VC	C	N	D	VC	C	N	D	VC	C	N	D	VC	C	N	D	VC	C	N	D
A	0,98	0,95	0,92	0,88	0,96	0,93	0,89	0,83	0,95	0,91	0,87	0,80	0,94	0,89	0,84	0,78	0,93	0,87	0,82	0,75	0,92	0,85	0,79	0,73
B	0,96	0,95	0,91	0,88	0,95	0,90	0,86	0,83	0,94	0,87	0,83	0,79	0,92	0,84	0,80	0,75	0,91	0,82	0,76	0,71	0,89	0,79	0,74	0,68
C	0,95	0,93	0,89	0,85	0,94	0,89	0,81	0,75	0,93	0,84	0,74	0,66	0,91	0,80	0,69	0,59	0,89	0,77	0,64	0,54	0,87	0,74	0,61	0,52
D	0,94	0,92	0,87	0,83	0,94	0,88	0,82	0,77	0,93	0,85	0,79	0,73	0,91	0,83	0,77	0,71	0,90	0,81	0,75	0,68	0,89	0,79	0,73	0,65
E	0,94	0,96	0,93	0,91	0,96	0,94	0,90	0,86	0,92	0,92	0,88	0,83	0,93	0,91	0,86	0,81	0,92	0,90	0,85	0,80	0,92	0,90	0,84	0,79
F	0,94	0,92	0,89	0,85	0,93	0,86	0,81	0,74	0,91	0,81	0,73	0,65	0,88	0,77	0,66	0,57	0,86	0,73	0,60	0,51	0,85	0,70	0,55	0,45
G	1,00	1,00	0,99	0,98	1,00	0,99	0,96	0,93	0,99	0,97	0,94	0,89	0,99	0,96	0,92	0,87	0,98	0,95	0,91	0,86	0,98	0,95	0,90	0,85

Table 3.6 : RSMF values according to CEN/TR 15193-2:2017

Reflectances ceiling/walls/floor	Time [years]	0,5	1,0	1,5	2,0	2,5	3,0	3,5	4,0	4,5	5,0	5,5	6,0
	environment	room surface maintenance factors											
0,80/0,70/0,20	very clean	0,97	0,96	0,95	0,95	0,95	0,95	0,95	0,95	0,95	0,95	0,95	0,95
	clean	0,93	0,92	0,91	0,91	0,91	0,91	0,91	0,91	0,91	0,91	0,91	0,91
	normal	0,88	0,86	0,86	0,85	0,85	0,85	0,85	0,85	0,85	0,85	0,85	0,85
	dirty	0,81	0,80	0,80	0,80	0,80	0,80	0,80	0,80	0,80	0,80	0,80	0,80
0,80/0,50/0,20	very clean	0,98	0,97	0,97	0,97	0,97	0,97	0,97	0,97	0,97	0,97	0,97	0,97
	clean	0,95	0,94	0,94	0,94	0,94	0,94	0,94	0,94	0,94	0,94	0,94	0,94
	normal	0,91	0,90	0,90	0,90	0,90	0,90	0,90	0,90	0,90	0,90	0,90	0,90
	dirty	0,86	0,85	0,85	0,85	0,85	0,85	0,85	0,85	0,85	0,85	0,85	0,85
0,80/0,30/0,20	very clean	0,99	0,98	0,98	0,98	0,98	0,98	0,98	0,98	0,98	0,98	0,98	0,98
	clean	0,97	0,96	0,96	0,96	0,96	0,96	0,96	0,96	0,96	0,96	0,96	0,96
	normal	0,94	0,93	0,93	0,93	0,93	0,93	0,93	0,93	0,93	0,93	0,93	0,93
	dirty	0,91	0,90	0,90	0,90	0,90	0,90	0,90	0,90	0,90	0,90	0,90	0,90
0,70/0,70/0,20	very clean	0,97	0,96	0,96	0,96	0,96	0,96	0,96	0,96	0,96	0,96	0,96	0,96
	clean	0,94	0,92	0,92	0,92	0,92	0,92	0,92	0,92	0,92	0,92	0,92	0,92
	normal	0,89	0,87	0,87	0,87	0,87	0,87	0,87	0,87	0,87	0,87	0,87	0,87
	dirty	0,83	0,81	0,81	0,81	0,81	0,81	0,81	0,81	0,81	0,81	0,81	0,81
0,70/0,50/0,20	very clean	0,98	0,97	0,97	0,97	0,97	0,97	0,97	0,97	0,97	0,97	0,97	0,97
	clean	0,96	0,95	0,94	0,94	0,94	0,94	0,94	0,94	0,94	0,94	0,94	0,94
	normal	0,92	0,91	0,90	0,90	0,90	0,90	0,90	0,90	0,90	0,90	0,90	0,90
	dirty	0,87	0,86	0,86	0,86	0,86	0,86	0,86	0,86	0,86	0,86	0,86	0,86

3.6.1.5 Luminaire Maintenance Factor (LMF)

The rate at which dirt is deposited depends on the construction of the luminaire and on the extent to which dirt is present in the atmosphere, which in turn is related to the nature of the dirt generated in the specific environment. The values were obtained from BS EN 15193.

Table 3.7 : LMF values for indoor use according to CEN/TR 15193-2:2017

Elapsed time between cleanings in years	0,5				1,0				1,5				2,0				2,5				3,0			
Luminaire type	Environment																							
	VC	C	N	D	VC	C	N	D	VC	C	N	D	VC	C	N	D	VC	C	N	D	VC	C	N	D
A	0,98	0,95	0,92	0,88	0,96	0,93	0,89	0,83	0,95	0,91	0,87	0,80	0,94	0,89	0,84	0,78	0,93	0,87	0,82	0,75	0,92	0,85	0,79	0,73
B	0,96	0,95	0,91	0,88	0,95	0,90	0,86	0,83	0,94	0,87	0,83	0,79	0,92	0,84	0,80	0,75	0,91	0,82	0,76	0,71	0,89	0,79	0,74	0,68
C	0,95	0,93	0,89	0,85	0,94	0,89	0,81	0,75	0,93	0,84	0,74	0,66	0,91	0,80	0,69	0,59	0,89	0,77	0,64	0,54	0,87	0,74	0,61	0,52
D	0,94	0,92	0,87	0,83	0,94	0,88	0,82	0,77	0,93	0,85	0,79	0,73	0,91	0,83	0,77	0,71	0,90	0,81	0,75	0,68	0,89	0,79	0,73	0,65
E	0,94	0,96	0,93	0,91	0,96	0,94	0,90	0,86	0,92	0,92	0,88	0,83	0,93	0,91	0,86	0,81	0,92	0,90	0,85	0,80	0,92	0,90	0,84	0,79
F	0,94	0,92	0,89	0,85	0,93	0,86	0,81	0,74	0,91	0,81	0,73	0,65	0,88	0,77	0,66	0,57	0,86	0,73	0,60	0,51	0,85	0,70	0,55	0,45
G	1,00	1,00	0,99	0,98	1,00	0,99	0,96	0,93	0,99	0,97	0,94	0,89	0,99	0,96	0,92	0,87	0,98	0,95	0,91	0,86	0,98	0,95	0,90	0,85

3.6.1.6 Lamp Survival Factor (LSF)

Manufacturers' data will give the percentage of lamp failures for a specific number of operation hours and is only applicable where group lamp replacement, without spot replacement, is to be carried out. These data will also be based on assumptions such as switching cycle, supply voltage and control gear. In this study LSF was assumed to be 1 considering spot replacements are done for defective luminaires.

3.6.1.7 Thermal adjustment factor for operating temperatures other than 25 °C

Performance characteristics of LED light sources are specified for a rated current and for an LED die junction temperature of 25°C. Most LEDs operate well above 25°C in real world applications. The light output from an LED light source decreases with increasing LED die junction temperature. Therefore, LLMF values given by the manufacturers should reflect this fact. Surprisingly, not many manufacturers have included this in the datasheet. One manufacturer's datasheet was chosen to demonstrate this in the study.

3.6.1.8 Control gear failure rate

Most common reason for LED luminaire failures is not the failure of the light engine, but the failure of the control gear/ driver. Manufacturers' datasheet should indicate this failure rate. To compensate for the driver failure, number of luminaires should be increased, which is not a quite efficient method. In this study, it was assumed the failed drivers will be replaced on the spot similar to the spot replacement of defective luminaires. Therefore, control gear failure rate was assumed to be 1.

3.6.2 System efficacy

With LED, the system efficacy is determined by measuring the total luminaire lumens and input watts.

$$\text{Efficacy } (\eta)=\frac{\text{luminaire lumens (F)}}{\text{input watts (W)}}\ \text{lm/W} \qquad (3.8)$$

3.6.3 Lighting power density (LPD)

LPD is given by,

$$\text{LPD}=\frac{\text{total connected load for all lighting systems in the building}}{\text{gross lighted floor area of the building}}$$

$$LPD = \frac{N \times W}{A} \tag{3.9}$$

3.6.4 Relationship between LPD and Efficacy

By rearranging the LPD equation and required number of luminaires equation,

$$LPD = \frac{N \times W}{A}$$

$$N = \frac{E \times A}{F \times UF \times MF}$$

Substituting for N in LPD equation,

$$LPD = \frac{E \times A}{F \times UF \times MF} \frac{W}{A}$$

$$LPD = \frac{E \times W}{F \times UF \times MF}$$

Also,

$$\eta = \frac{F}{W}$$

Then,

$$LPD = \frac{E}{\eta \times UF \times MF} \tag{3.10}$$

Therefore, to comply with LPD allowances given in building code,

$$LPD_{Installation} \leq LPD_{Recommended}$$

$$\frac{E}{\eta \times UF \times MF} \leq LPD_{Recommended}$$

$$\eta \geq \frac{E}{LPD_{Recommended} \times UF \times MF} \tag{3.11}$$

3.6.5 Design lifetime

The average time of a building for the next refurbishment is considered as the design lifetime (for example an office building with 20 years renovation period is taken as 20 years for design lifetime).

Design lifetime=Annual operating hours × years of operation

Annual operating hours were chosen from Table G.1 of EN 15193: Energy performance of buildings — Energy requirements for lighting.

Table 3.8 : Default annual operating hours according to BS EN 15193

Building types	Default annual operating hours		
	t_D	t_N	t_O
Offices	2 250	250	2 500
Education buildings	1 800	200	2 000
Hospitals	3 000	2 000	5 000
Hotels	3 000	2 000	5 000
Restaurants	1 250	1 250	2 500
Sports facilities	2 000	2 000	4 000
Wholesale and retail services	3 000	2 000	5 000
Manufacturing factories	2 500	1 500	4 000
NOTE National values may be substituted where necessary.			

The need for replacing the group of luminaires may never encounter during the years of operation of the lighting system before a major refurbishment due to the very long lifetime of an LED luminaire. Some LED luminaires with relatively low lifetime may need replacing the luminaires after a certain years of operation before they cannot maintain the required illumination. A considerable cost elimination is possible with a luminaire with longer lifetime.

Also, energy and cost savings from dimming the luminaires can only be accurately calculated when the total years of operation is considered. Therefore, lifetime considerations were used in calculations to yield meaningful results.

3.6.6 Energy consumption

Energy consumption of the lighting system for the total years of operation of the lighting system was calculated.

For a non-dimmable lighting system this can be achieved by,

Energy consumption per luminaire =Wattage ×annual operating hours × years of operation (3.12)

3.6.7 Energy consumption for a dimmable luminaire

For a dimmable lighting system, since the energy consumption in each year is different, this can be achieved by,

Energy consumption per luminaire= $\sum_{0}^{n} W \times t$ (3.13)

n = years of operation

t = time of operation

In this study, for dimmable luminaires, input electric power to the luminaire was assumed to regulate to follow the pattern of maintenance plan throughout the years of operation. Therefore, the higher illumination levels incurred by the additional number of luminaires which were required to compensate for maintenance factor and room geometry were balanced.

Since the full light output of luminaire was not required at all times, the required lumen output from the dimmable luminaire at a given time was calculated by,

Required Lumens (F_r) = $\frac{E \times A}{N \times MF \times UF}$ (3.14)

Required wattage corresponding to the above luminous flux F_r was calculate by, Required Wattage (W_r) = $\frac{F_r}{\eta}$ (3.15)

η = luminous efficacy

3.7 Cost calculations

3.7.1 Initial cost

Initial cost = N × (luminaire cost + installation cost) (3.16)

3.7.2 Luminaire replacement cost

When the lifetime of the luminaire is less than the design lifetime, one or more luminaire replacements will be required. The replacement cost was calculated using below formula.

$$\text{Luminaire replacement cost} = \left[N \times \frac{\text{design lifetime}}{\text{luminaire lifetime}} - 1\right] \times \text{initial cost}$$

(3.17)

3.7.3 Room surface maintenance cost

Labour cost was considered as 250Rs/hour. Room surface area (ceiling, walls, floor) that is cleaned was considered as 50m^2/hour to calculate the room maintenance cost. Then,

$$\text{Room surface maintenance cost} = C_{labour/h} \times \frac{A_s}{A_{clean/h}} \times \frac{Y}{T_R} \quad (3.18)$$

$L_{abour/h}$= cleaning labour cost per hour

A_s = total surface area of room

$C_{lean/h}$ = surface area cleaned per hour

Y = years of operation

T_R = Room maintenance interval

3.7.4 Luminaire cleaning cost

Labour cost was considered as 250Rs/hour. Luminaires cleaned was considered as 50luminaires/hour.

Then,

$$\text{Luminaire maintenance cost} = C_{labour/h} \times \frac{N}{L_{clean/h}} \times \frac{Y}{T_L} \qquad (3.19)$$

$L_{abour/h}$= cleaning labour cost per hour
$C_{lean/h}$ = luminaires cleaned per hour
Y = years of operation
T_L = Luminaire maintenance interval

3.7.5 Energy cost

Total energy cost for the design lifetime was calculated using below formulae.

$$\text{Energy cost} = \text{Energy consumption over lifetime} \times \text{energy rate} \qquad (3.20)$$

$$\text{Maximum demand charge} = \text{Maximum demand rate} \times \frac{N \times W_r}{\text{power factor}} \qquad (3.21)$$

$$\text{Total energy cost} = \text{Energy cost} + \text{Maximum demand charge} \qquad (3.22)$$

3.7.6 Operation cost

Operation cost was considered as the sum of all the other cost components except initial cost.

Running cost = Luminaire replacement cost + Room surface maintenance cost + Luminaire maintenance cost + Total energy cost (3.23)

3.7.7 Total cost for design lifetime

Sum of all the cost components incurred from initial stage to final stage was considered as the total cost for design lifetime.

$$\text{Total cost} = \text{Initial cost} + \text{Operation cost} \qquad (3.24)$$

CHAPTER 4

4 ANALYSIS AND RESULTS

4.1 Study on LED luminaires in Sri Lankan market

LED lamps and luminaires in Sri Lankan retail market are mostly used by households. Other than very few, most of these lamps and luminaires are not provided by reputed manufacturers where a customer can visit the manufacturer's website and obtain the necessary information. LED lamps and luminaires for large scale projects are imported by a number of suppliers as well. From the quality perspective there is a wide range of LED luminaires from the lowest quality to highest quality. From the samples chosen for the study, there were many variations in technical specifications between the same types of LED luminaire depending on the manufacturer/brand. Also, some suppliers had a wide range of products from lowest quality to highest quality within a wide range of prices. Following parameters of LED luminaires from different manufacturers were studied.

1. Rated input power (W)
2. Power factor
3. Initial luminous flux (lm)
4. Luminous efficacy (lm/W)
5. Photometric data
6. Correlated colour temperature (K)
7. Colour rendering index (CRI)
8. Beam Angle
9. Rated median useful life Lx
10. Lamp survival factor
11. Driver failure rate
12. Ambient temperature related to performance of the luminaire (˚C)
13. Operating temp. range (˚C)
14. Effect of ambient temperature on the performance of luminaire

15. Mounting method
16. IP rating
17. Warranty

4.2 Determine the minimum efficacy requirement

Using the Equation 3.11, minimum efficacy related to the Lighting Power Density requirement recommended by "Code of practice for Energy Efficient Buildings in Sri Lanka" and ASHRAE 90.1 Energy Standard for Buildings Except Low-Rise Residential Buildings was obtained for the four types of building spaces.

First, maintenance factors were determined based on the luminaire class, environmental condition, cleaning intervals, reflectance of room surfaces as given in BS15193. Reflectance of ceiling/wall/floor were considered as 70/50/20 for all cases. LSF was considered as 1, assuming spot replacements are carried out. Based on these calculations, it was observed that the maintenance factors were between 0.68 – 0.76 before applying LLMF. Two values of LLMF were used to compare the results. Utilization factor was taken as 0.9 for all types of luminaires by considering the average values for LED luminaires.

Table 4.1 : LMF and RMF values for building spaces

Building space	Luminaire Class	Environmental condition	Luminaire Cleaning Interval	LMF	Room Cleaning Interval	RMF
Office	D - IP2X	Clean	3	0.79	3	0.94
School/ University	D - IP2X	Clean	3	0.79	3	0.94
Warehouse	E - IP5X	Normal	3	0.84	6	0.90
Manufacturing Facility	E - IP5X	Dirty	3	0.79	6	0.86

Table 4.2 : MF values for building spaces when LLMF=0.7

Building space	LMF×RMF	LLMF	MF = LMF×RMF× LSF×LLMF
Office	0.74	0.70	0.52
School/University	0.74	0.70	0.52
Warehouse	0.76	0.70	0.53
Manufacturing Facility	0.68	0.70	0.48

Table 4.3 : Calculated minimum efficacy requirement when LLMF=0.7

Building space	Length (m)	Width (m)	Luminaire mounting height (m)	Work plane height (m)	Room Index	Utilization Factor	Recommended Illumination (lux)	Maintenance Factor	Recommended LPD (W/m^2)		Minimum efficacy required (lm/W)
Office	16	16	2.8	0.8	4.0	0.9	500	0.52	2007	10.76	99
									2010	9.69	110
									2013	8.83	121
									2016	8.50	126
									2019	6.89	155
School/University	16	16	2.8	0.8	4.0	0.9	500	0.52	2007	12.92	83
									2010	10.66	100
									2013	9.36	114
									2016	8.72	123
									2019	7.75	138
Warehouse	32	32	8.8	0	1.8	0.9	200	0.53	2007	8.61	49
									2010	7.10	59
									2013	7.10	59
									2016	5.17	81
									2019	4.84	87
Manufacturing Facility	32	32	8.8	0	1.8	0.9	750	0.48	2007	13.99	125
									2010	11.95	147
									2013	12.59	139
									2016	9.69	181
									2019	8.83	198

Table 4.4 : Required minimum efficacy for lighting in different building spaces when LLMF=0.7

Building space	Year				
	2007	2010	2013	2016	2019
Office	99	110	121	126	155
School/University	83	100	114	123	138
Warehouse	49	59	59	81	87
Manufacturing Facility	125	147	139	181	198

Table 4.5 : MF values for building spaces when LLMF=0.9

Building space	LMF×RMF	LLMF	MF = LMF×RMF× LSF×LLMF
Office	0.74	0.90	0.67
School/University	0.74	0.90	0.67
Warehouse	0.76	0.90	0.68
Manufacturing Facility	0.68	0.90	0.61

Table 4.6 : Calculated minimum efficacy requirement when LLMF=0.9

Building space	Length (m)	Width (m)	Luminaire mounting height (m)	Work plane height (m)	Room Index	Utilization Factor	Recommended Illumination (lux)	Maintenance Factor	Recommended LPD (W/m^2)		Minimum efficacy required (lm/W)
Office	16	16	2.8	0.8	4.0	0.9	500	0.67	2007	10.76	76
									2010	9.69	85
									2013	8.83	93
									2016	8.50	97
									2019	6.89	119
School/University	16	16	2.8	0.8	4.0	0.9	500	0.67	2007	12.92	64
									2010	10.66	78

									2013	9.36	89
									2016	8.72	95
									2019	7.75	107
Warehouse	32	32	8.8	0	1.8	0.9	200	0.68	2007	8.61	38
									2010	7.10	46
									2013	7.10	46
									2016	5.17	63
									2019	4.84	68
Manufacturing Facility	32	32	8.8	0	1.8	0.9	750	0.61	2007	13.99	98
									2010	11.95	114
									2013	12.59	109
									2016	9.69	141
									2019	8.83	155

Table 4.7 : Required minimum efficacy for lighting in different building spaces when LLMF=0.9

Building space	Year				
	2007	2010	2013	2016	2019
Office	76	85	93	97	119
School/University	64	78	89	95	107
Warehouse	38	46	46	63	68
Manufacturing Facility	98	114	109	141	155

When LLMF was 0.7 which is the minimum value of lumen maintenance ratio within the design lifetime, it was observed that the minimum efficacy values obtained were very high based on the maintenance factors given in BS15193 and recommended lux levels. However, in School/University and Warehouse buildings, the obtained values were reasonable since the required light levels were less.

When LLMF was 0.9, the obtained efficacy values were reasonable and matched with the current efficacy values of luminaires. However, in School/University and Warehouse buildings, the obtained values were very low since the required light levels, but these values were impractical because LEDs are way more efficient than this.

Due to this ambiguity, three interpretations of LLMF values were used in the study.

4.3 Case study: Office space

A very common integrated LED luminaire in the panel form intended as an alternative to tubular fluorescent based general purpose troffer/recessed luminaires. This type of luminaire is commonly used in places where uniform light distribution is required such as offices. Performance of five different luminaires from five different manufacturers were compared. Results are shown in Table 4.8.

While the efficacy, CRI and power factor were adequately specified in all the luminaires, lifetime specifications were not clearly mentioned in the datasheets in some luminaires.

Since the ambient temperature inside an office environment is normally kept below 26 °C by air conditioning, the temperature related to performance specifications of the luminaire being 25°C will not cause major differences in lamp lumen maintenance or lifetime.

4.3.1 Summary of Lifetime Analysis

Following general information regarding the building space were considered for the study. Results are shown in Table 4.9.

A total lifetime cost analysis was done to evaluate the performance of each luminaire. Three luminaires from different manufacturers were selected. Since three methods of deriving LLMF was discussed in the methodology, results were obtained for all three methods. Results are shown in Table 4.10.

Table 4.8 : Luminaire performance parameters for integrated LED Panel Lights from different manufacturers

Parameter	Luminaire				
	LM1	LM2	LM3	LM4	LM5
Rated input power (W)	36	28.5	40	36	37
Power factor	0.9	0.9	0.9	0.9	0.97
Initial luminous flux (lm)	3600	3400	3600	3611	3400
Efficacy (lm/W)	98	121	90	-	-
Unified glare rating	19	-	-	-	-
Correlated colour temperature (K)	4000K	4000K	4000K	4000K	4000K
Beam Angle	81°×85°	80°	120°	120°	110°
Colour rendering index (CRI)	>80	>80	>80	>80	>80
Rated median useful life Lx	L70 70,000 h, L80 50,000 h, L90 15,000 h	L70 50,000 h	L70 50,000 h, L80 40,000 h, L90 30,000 h	-	30,000 h
Control gear failure rate at median useful lifetime	0.05%	-	-	-	-
Ambient temperature related to performance of the luminaire (˚C)	25	25	25	-	-
Operating temp. range (˚C)	+10 to +40	+10 to +40	-10 to +45	-	-

Table 4.9 : General information – Office space

General data			
Building type	Open office		
Ambient condition	Clean (C)		
Annual operating hours	2500 Hrs		
Time for refurbishment	20 years		
Design Lifetime	50,000 Hrs		
Dimensions	L:16m	W:16m	H:2.8m
Luminaire Mounting Height	2.8m		
Work plane height	0.8m		
Room Index (K)	4.0		
Room cavity ratio (RCR)	1.2		
Design illumination	500lux		
Cleaning labour cost	250 Rs/hour		
Area cleaned per hour	10 m^2/hour		
Luminaires cleaned per hour	10 luminaires/hour		
Luminaire installation cost	250Rs		
Energy rate	21.8 Rs/kWh		
Maximum demand rate	1100 Rs/kVA		

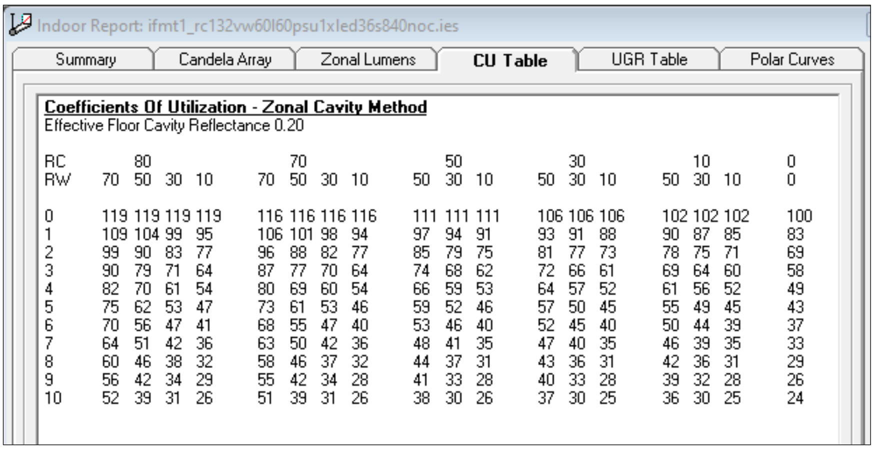
Table 4.10 : Luminaire information – LED Panel lights

Luminaire information			
	Luminaire 1	Luminaire 2	Luminaire 3
Wattage (W)	33	30	36
Dimmable	No	No	No
Lumens (Lm)	3600	3000	3400
Efficacy (Lm/W)	109	100	94
UF	0.98	1.08	0.98
Lifetime (Hours)	50000	50000	30000
Power factor	0.9	0.9	0.97
IP Rating	IP20	IP20	IP20
Fixture cost (Rs.)	25000	8500	7500

4.3.1.1 Utilization factor calculation

Utilization factor was obtained using Photometric Toolbox-2.7 and the ies file of the luminaire.

Luminaire 1: UF table was not available in the luminaire datasheet. Therefore, ies file of the luminaire was used to determine the UF.


Indoor Report: ifmt1_rc132vw60l60psu1xled36s840noc.ies

Summary | Candela Array | Zonal Lumens | CU Table | UGR Table | Polar Curves

Coefficients Of Utilization - Zonal Cavity Method
Effective Floor Cavity Reflectance 0.20

RC	80				70				50			30			10			0
RW	70	50	30	10	70	50	30	10	50	30	10	50	30	10	50	30	10	0
0	119	119	119	119	116	116	116	116	111	111	111	106	106	106	102	102	102	100
1	109	104	99	95	106	101	98	94	97	94	91	93	91	88	90	87	85	83
2	99	90	83	77	96	88	82	77	85	79	75	81	77	73	78	75	71	69
3	90	79	71	64	87	77	70	64	74	68	62	72	66	61	69	64	60	58
4	82	70	61	54	80	69	60	54	66	59	53	64	57	52	61	56	52	49
5	75	62	53	47	73	61	53	46	59	52	46	57	50	45	55	49	45	43
6	70	56	47	41	68	55	47	40	53	46	40	52	45	40	50	44	39	37
7	64	51	42	36	63	50	42	36	48	41	35	47	40	35	46	39	35	33
8	60	46	38	32	58	46	37	32	44	37	31	43	36	31	42	36	31	29
9	56	42	34	29	55	42	34	28	41	33	28	40	33	28	39	32	28	26
10	52	39	31	26	51	39	31	26	38	30	26	37	30	25	36	30	25	24

Figure 4.1 : Luminaire 1 UF table generated from Photometric Toolbox

By interpolating the values for RCR =1.2,

$$UF = 101- \left(\frac{101-88}{5}\right)*1$$

$$= 98.4$$

Luminaire 2: UF table provided in the manufacturer's datasheet was used for calculation.

Coefficients Of Utilization – Zonal Cavity Method				
RCC %:	80			
RW %:	70	50	30	0
RCR: 0	119	119	119	119
1	110	106	102	98
2	101	93	87	82
3	93	83	76	70
4	85	74	66	60
5	79	67	58	52
6	73	60	52	46
7	68	55	47	41
8	63	50	42	37
9	59	46	38	33
10	55	43	35	30

Effective Floor Cavity Reflectance: 20%

Figure 4.2: Luminaire 2 UF table provided by the manufacturer's datasheet

By interpolating the values for K=1.2,

$$UF =110- \left(\frac{110-101}{5}\right)*1$$

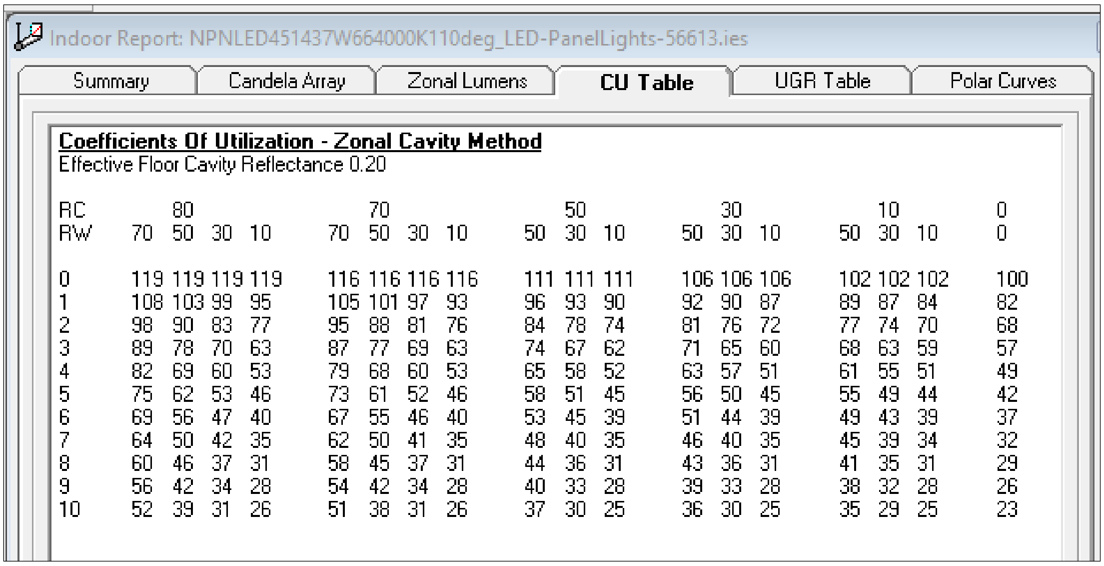
$$=108.2$$

Luminaire 3: UF table was not available in the luminaire datasheet. Therefore, ies file of the luminaire was used to find UF.

By interpolating the values for K=1.2,

$$UF =101- \left(\frac{101-88}{5}\right)*1$$

$$=98.4$$



Coefficients Of Utilization - Zonal Cavity Method
Effective Floor Cavity Reflectance 0.20

RC	80				70				50			30			10			0
RW	70	50	30	10	70	50	30	10	50	30	10	50	30	10	50	30	10	0
0	119	119	119	119	116	116	116	116	111	111	111	106	106	106	102	102	102	100
1	108	103	99	95	105	101	97	93	96	93	90	92	90	87	89	87	84	82
2	98	90	83	77	95	88	81	76	84	78	74	81	76	72	77	74	70	68
3	89	78	70	63	87	77	69	63	74	67	62	71	65	60	68	63	59	57
4	82	69	60	53	79	68	60	53	65	58	52	63	57	51	61	55	51	49
5	75	62	53	46	73	61	52	46	58	51	45	56	50	45	55	49	44	42
6	69	56	47	40	67	55	46	40	53	45	39	51	44	39	49	43	39	37
7	64	50	42	35	62	50	41	35	48	40	35	46	40	35	45	39	34	32
8	60	46	37	31	58	45	37	31	44	36	31	43	36	31	41	35	31	29
9	56	42	34	28	54	42	34	28	40	33	28	39	33	28	38	32	28	26
10	52	39	31	26	51	38	31	26	37	30	25	36	30	25	35	29	25	23

Figure 4.3 : Luminaire 3 UF table generated from Photometric Toolbox

Table 4.11 : Utilization factors

	Luminaire 1	Luminaire 2	Luminaire 3
UF	0.98	1.08	0.98

4.3.1.2 Method 1 - LLMF derived using the end of life light percentage and design lifetime

Table 4.12 : Summary of results – Office space (LLMF derived using the end of life light percentage and design lifetime)

	Luminaire 1	Luminaire 2	Luminaire 3
LLMF	0.75	0.7	0.7
MF	0.55	0.51	0.5
Lighting design			
Illumination	485	526	534
Max. illumination	881	1025	1042
Min. illumination	501	548	535

Number of luminaires	64	72	80
Cost analysis			
Initial cost	1,616,000	708,750	620,000
Maintenance cost	80,320	83,295	754,960
Energy cost	2,921,600	3,361,500	4,032,008
Total cost	4,617,920	4,153,545	5,406,968
Present Worth	-2,513,918	-1,739,938	-2,033,553
% Initial cost	35%	17.1%	11.5%
% Maintenance cost	1.74%	2.01%	14.0%
% Energy cost	63.3%	80.9%	74.6%
Energy analysis			
Energy consumption (kWh)	105,600	121,500	148,000
Design LPD	8.5	8.5	8.5
Actual LPD	8.25	9.49	11.56
Percentage LPD Variation	3%	-12%	-36%

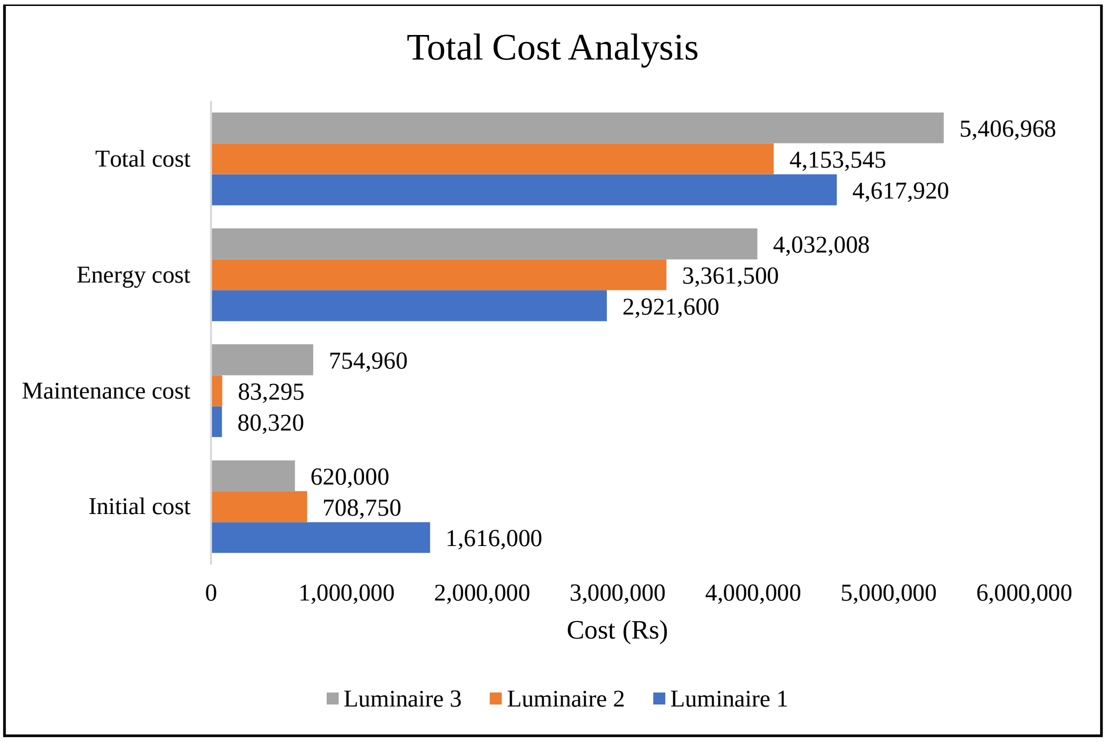


Figure 4.4 : Summary of total cost analysis – Office space

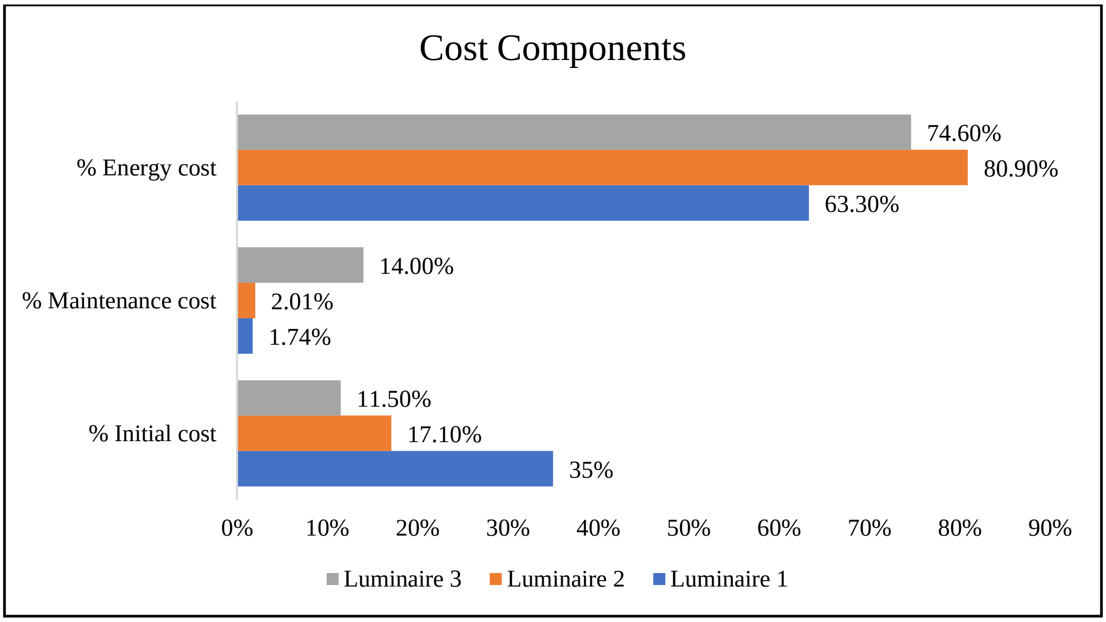


Figure 4.5 : Comparison of various cost components – Office space

4.3.1.2.1 Maintenance factors

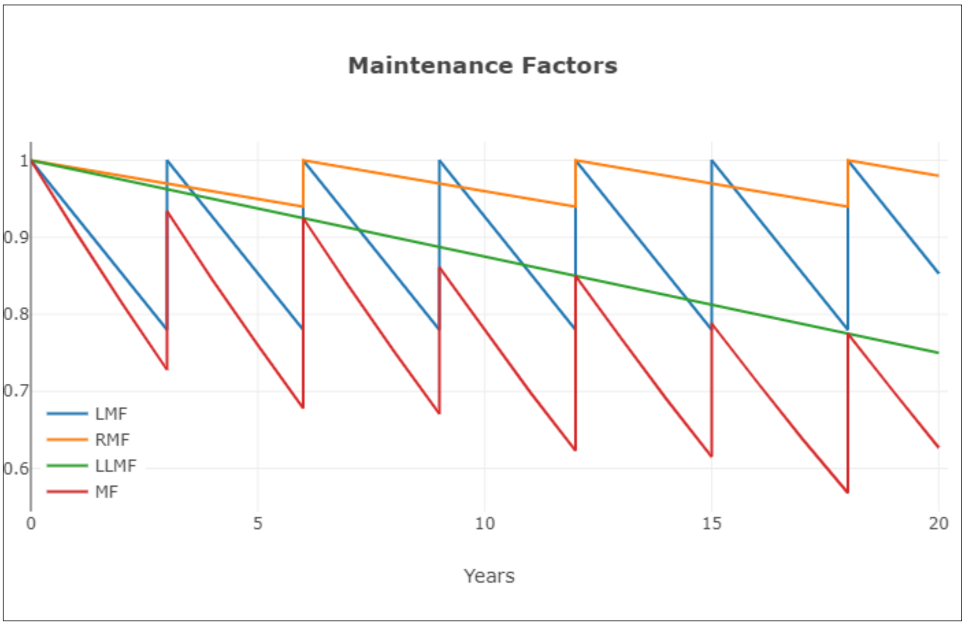


Figure 4.6 : Luminaire 1 Calculated MF- 0.55, Minimum MF obtained over the lifetime - 0.568

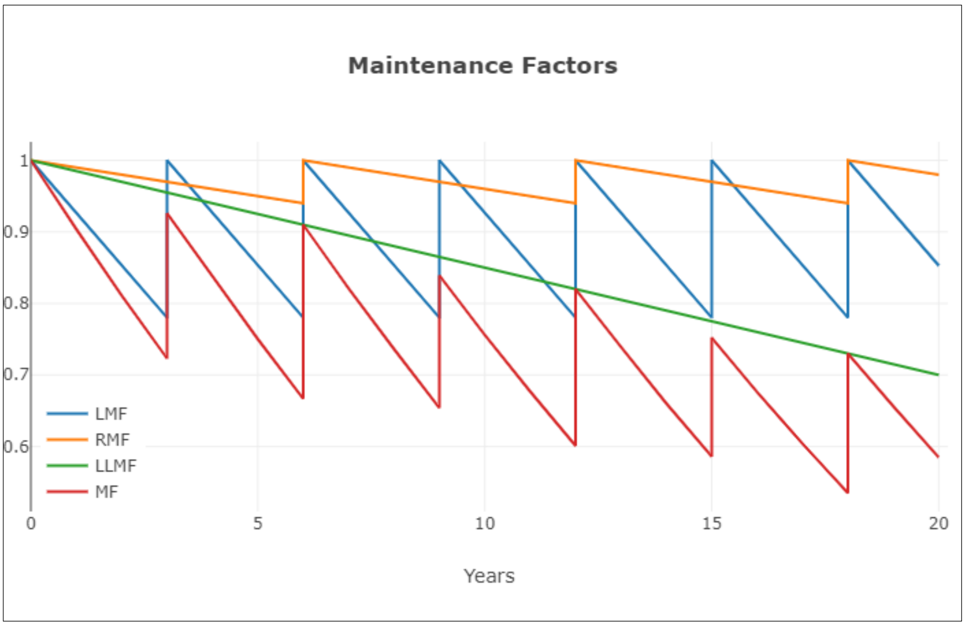


Figure 4.7 : Luminaire 2 Calculated MF- 0.51, Minimum MF obtained over the lifetime - 0.54

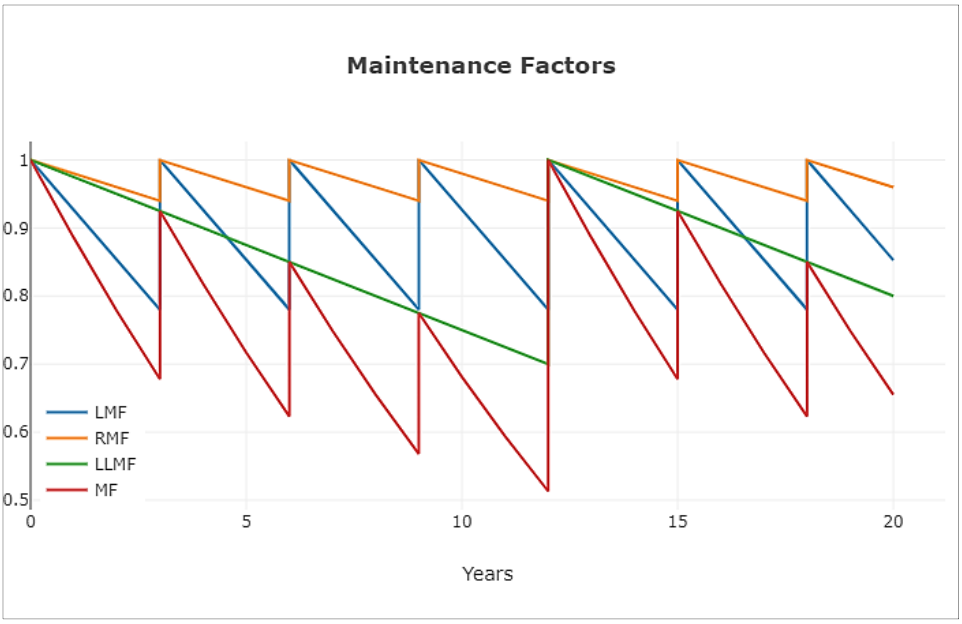


Figure 4.8 : Luminaire 3 Calculated MF- 0.51, Minimum MF obtained over the lifetime - 0.51

4.3.1.2.2 Maintained illumination

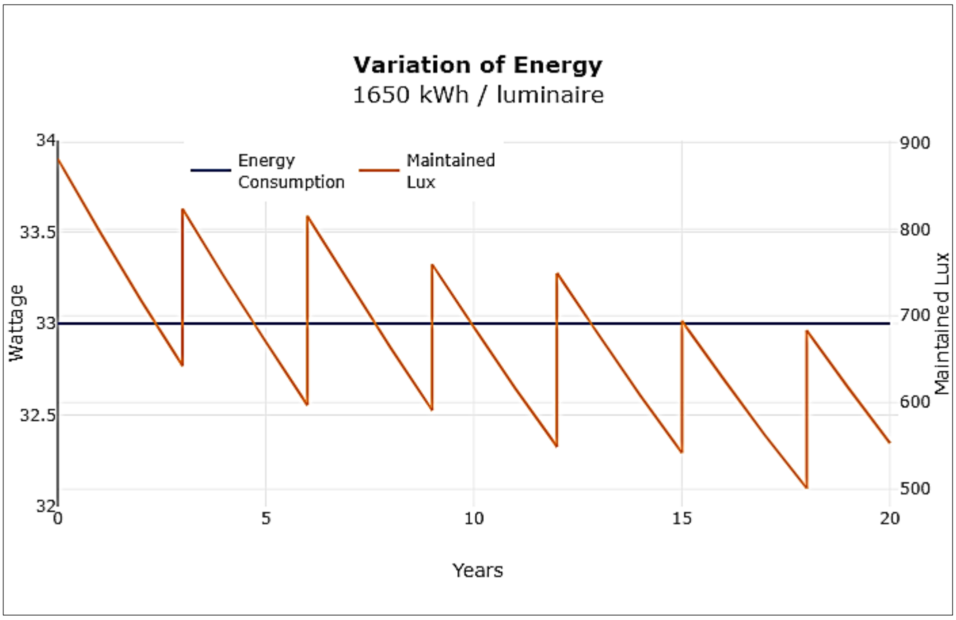


Figure 4.9 : Luminaire 1 Design illumination: 485 lux, Minimum illumination achieved over the lifetime: 501 lux

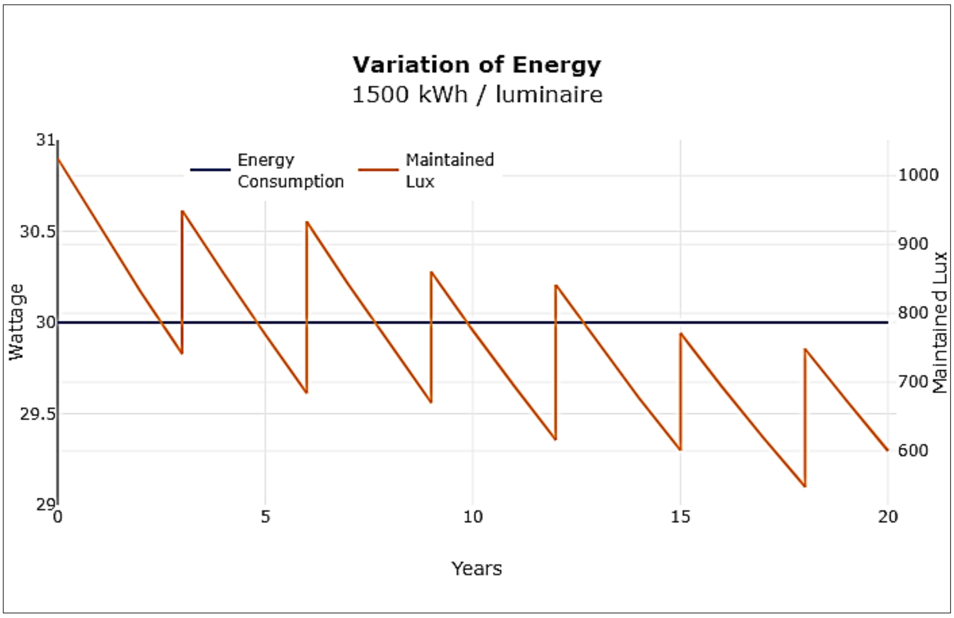


Figure 4.10 : Luminaire 2 Design illumination: 526 lux, Minimum illumination achieved over the lifetime: 548 lux

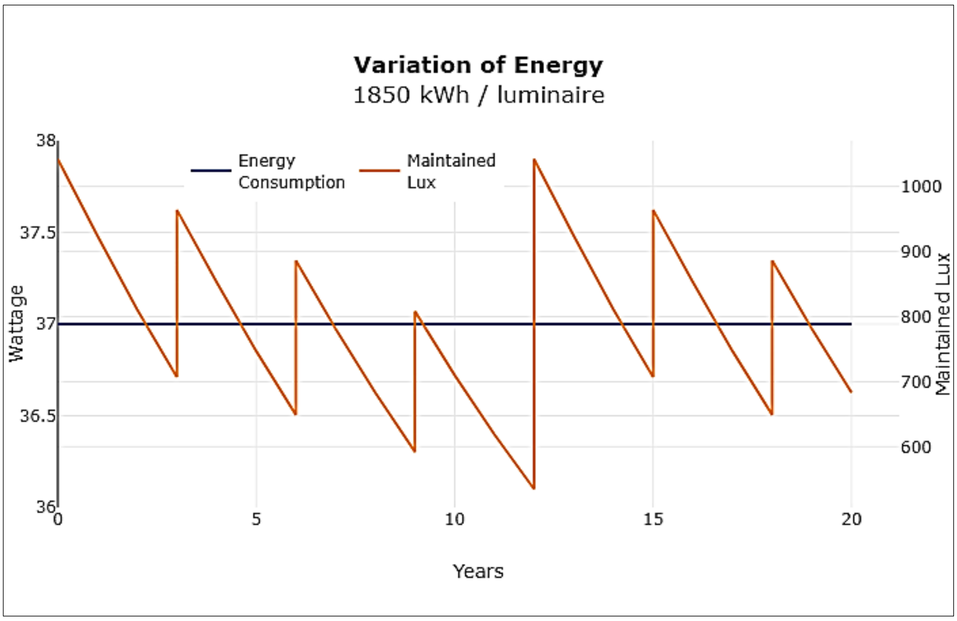


Figure 4.11 : Luminaire 3 Design illumination: 534 lux, Minimum illumination achieved over the lifetime: 535 lux

4.3.1.3 Method 2- LLMF = 0.7 for all luminaires

Table 4.13 : Summary of results – Office space (LLMF=0.7)

	Luminaire 1	Luminaire 2	Luminaire 3
LLMF	0.7	0.7	0.7
MF	0.51	0.51	0.5
Lighting design			
Illumination	546	526	534
Max. illumination	991	1025	1042
Min. illumination	563	548	535
Number of luminaires	72	72	80
Cost analysis			
Initial cost	1,818,000	708,750	620,000
Maintenance cost	81,720	83,295	754,960
Energy cost	3,286,800	3,361,500	4,032,008
Total cost	5,186,520	4,153,545	5,406,968
Present Worth	-2,826,229	-1,548,326	-2,033,553
% Initial cost	35.1%	17.1%	11.5%
% Maintenance cost	1.58%	2.01%	14.0%
% Energy cost	63.4%	80.9%	74.6%
Energy analysis			
Energy consumption (kWh)	118,800	121,500	148,000
Design LPD	8.5	8.5	8.5
Actual LPD	9.28	9.49	11.56
Percentage LPD Variation	-9%	-12%	-36%

4.3.1.4 Method 3 - LLMF derived using the mean lumen output to initial lumen output ratio

$$LLMF= \frac{\text{Mean lumen output}}{\text{Initial lumen output}}$$

Here**,** the mean light output stands for lumen output at the time corresponding to 40% of the design lifetime.

Therefore, LLMF can be obtained as the value corresponding to 20,000 Hrs since the design lifetime of the office building was considered as 50,000 Hrs.

Table 4.14 : Summary of results – Office space (LLMF derived using the mean lumen output to initial lumen output ratio)

	Luminaire 1	Luminaire 2	Luminaire 3
LLMF	0.9	0.88	0.88
MF	0.66	0.645	0.645
Lighting design			
Illumination	424	416	427
Max. illumination	771	810	834
Min. illumination	438	433	428
Number of luminaires	56	64	64
Cost analysis			
Initial cost	1,414,000	560,000	496,000
Maintenance cost	78,920	80,320	625,160
Energy cost	2,556,400	2,656,000	3,225,607
Total cost	4,049,320	3,296,320	3,853,767
Present Worth	-2,201,608	-1,378,005	-1,634,267
% Initial cost	34.9%	17%	11.4%
% Maintenance cost	1.95%	2.44%	14.4%

% Energy cost	63.1%	80.6%	74.2%
Energy analysis			
Energy consumption (kWh)	92,400	96,000	118,400
Design LPD	8.5	8.5	8.5
Actual LPD	7.72	7.5	9.25
Percentage LPD Variation	15%	12%	-9%

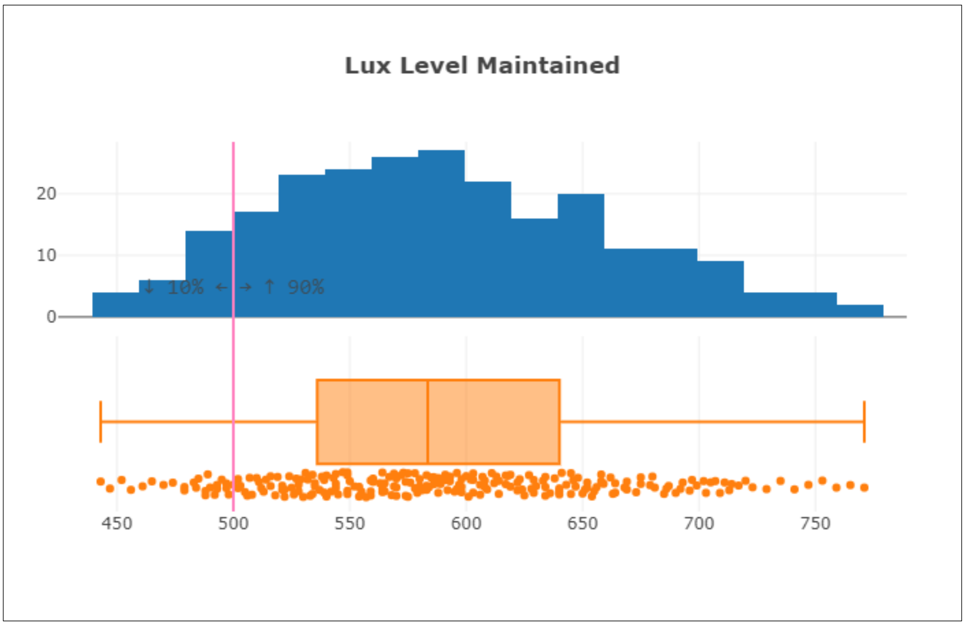


Figure 4.12 : Luminaire 1 Lux level maintenance histogram

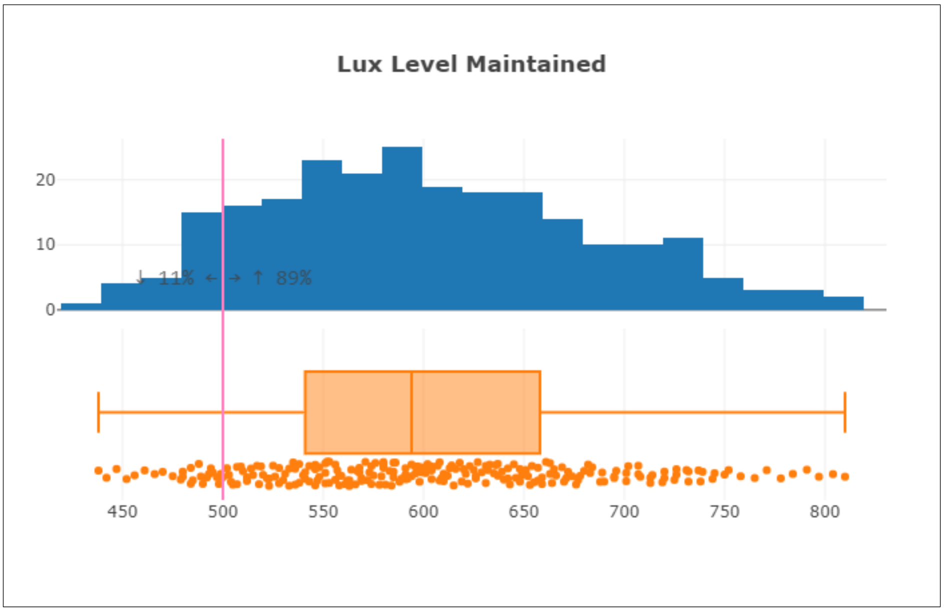


Figure 4.13 : Luminaire 2 Lux level maintenance histogram

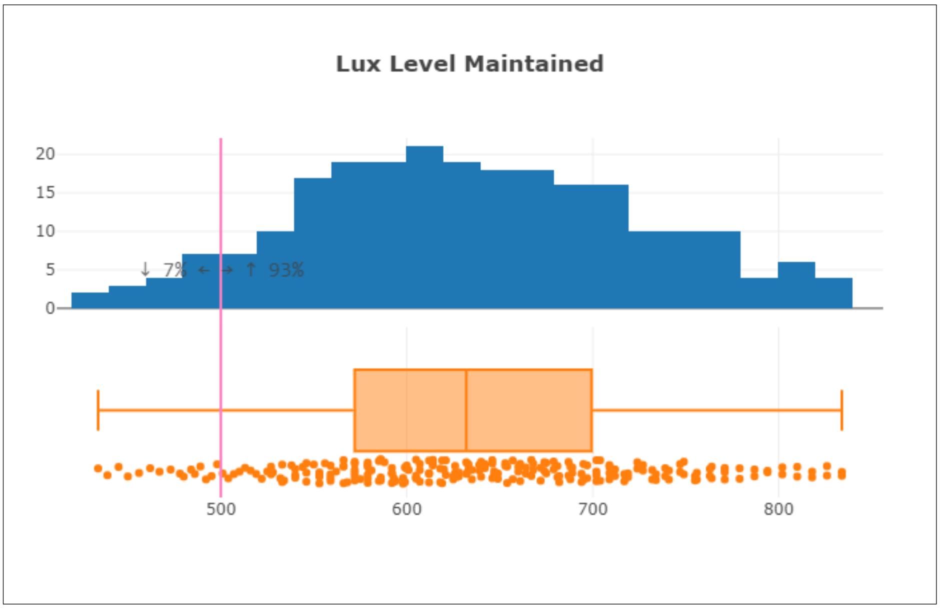


Figure 4.14 : Luminaire 3 Lux level maintenance histogram

4.3.1.5 Maintenance Factor 0.8

A general rule of thumb approach used in lighting design for office spaces is to use a maintenance factor of 0.8 regardless of the type of the luminaires used or maintenance cycles to determine the number of luminaires required.

Table 4.15 : Summary of results – Office space (MF=0.8)

	Luminaire 1	Luminaire 2	Luminaire 3
MF	0.8	0.8	0.8
Lighting design			
Illumination	364	318	327
Max. illumination	661	620	639
Min. illumination	375	332	328
Number of luminaires	48	49	49
Cost analysis			
Initial cost	1,212,000	428,750	379,750
Maintenance cost	77,520	77,695	509,285
Energy cost	2,191,200	2,033,500	2,469,605
Total cost	3,480,720	2,539,945	2,978,890
Present Worth	-1,889,298	-1,058,653	-1,259,937
% Initial cost	34.8%	16.9%	11.3%
% Maintenance cost	2.23%	3.06%	15.2%
% Energy cost	63%	80.1%	73.5%
Energy analysis			
Energy consumption (kWh)	79,200	73,500	90,650
Design LPD	8.5	8.5	8.5
Actual LPD	6.19	5.74	7.08
Percentage LPD Variation	27%	32%	17%

Even though the number of luminaires required was obtained by using MF of 0.8, the MF will follow the actual pattern as shown in Figure 4.15 : Maintenance factor variation with time and the actual light levels will follow this pattern.

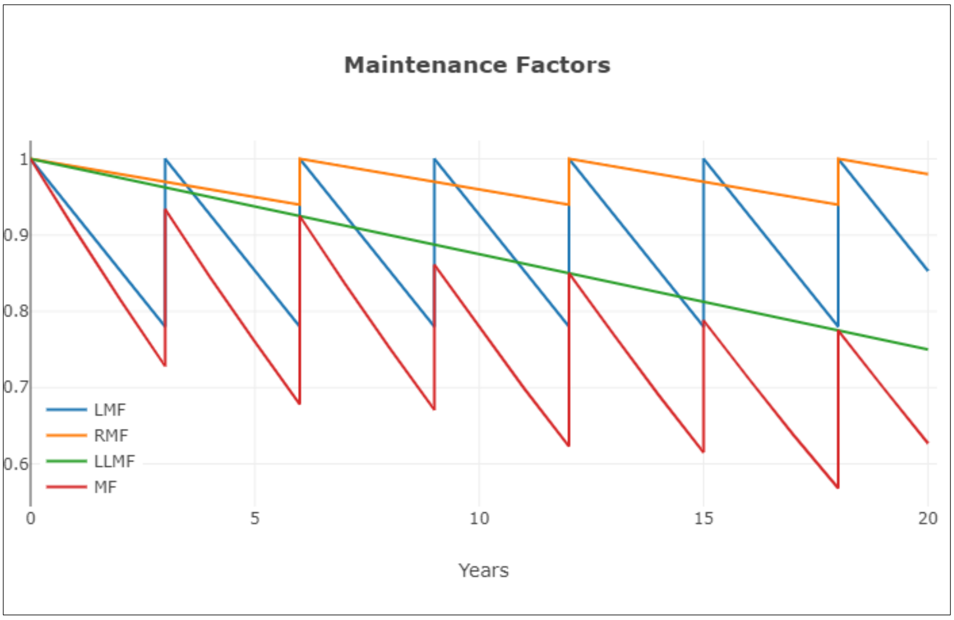


Figure 4.15 : Maintenance factor variation with time

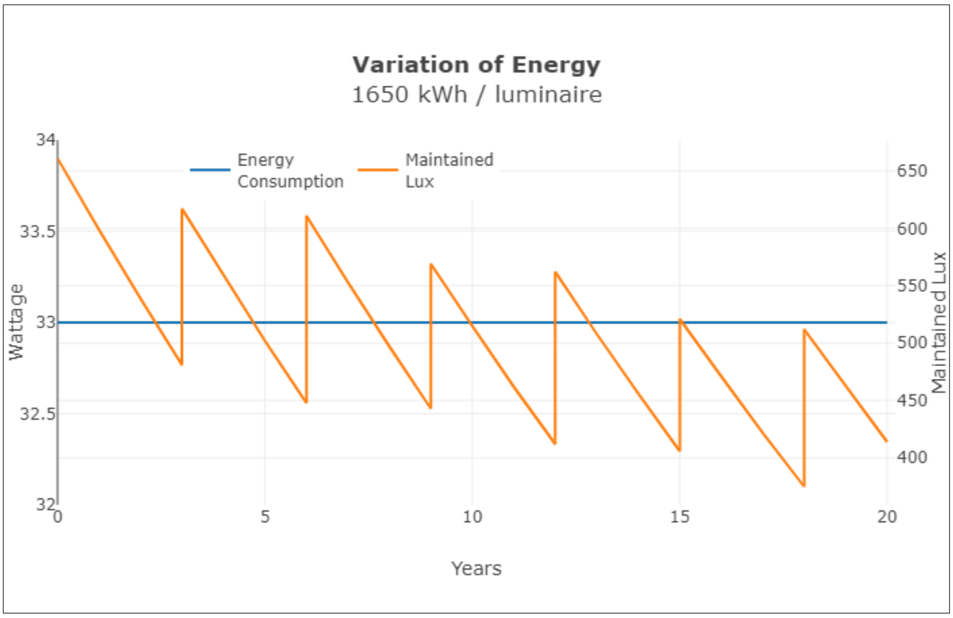


Figure 4.16 : Luminaire 1 Maintained illumination with time

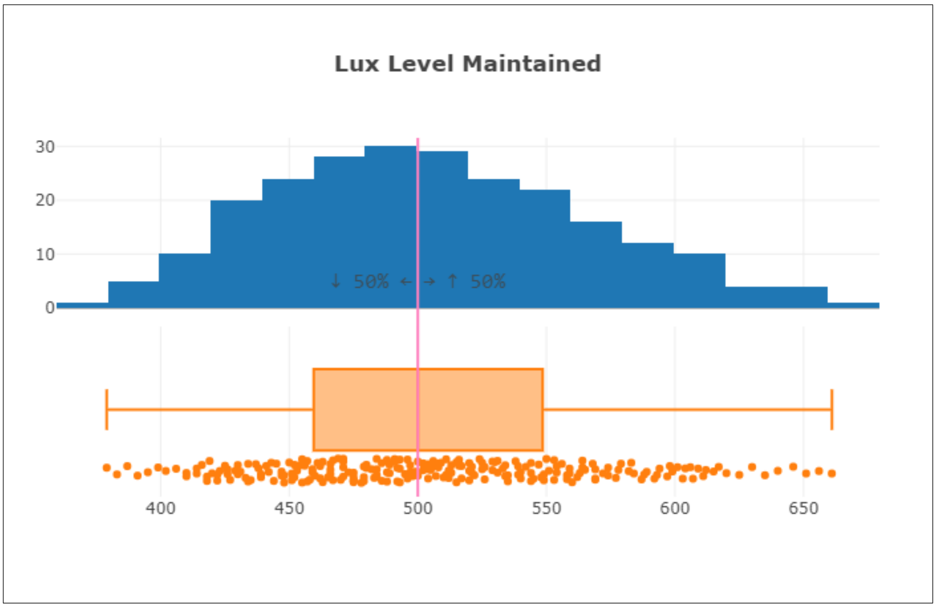


Figure 4.17 : Luminaire 1 Lux level maintenance histogram (50% of the time light levels are below 500)

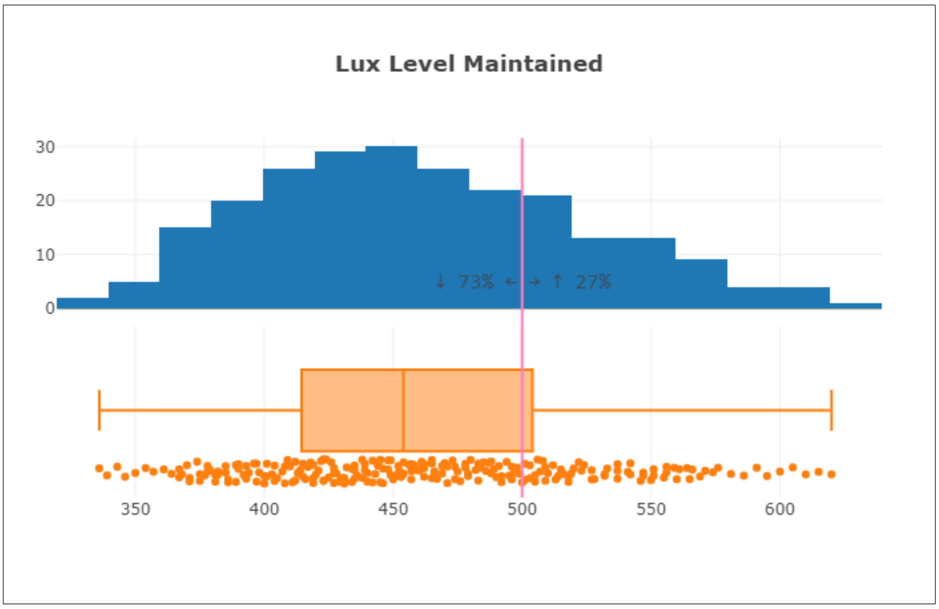


Figure 4.18 : Luminaire 2 Lux level maintenance histogram (73% of the time light levels are below 500)

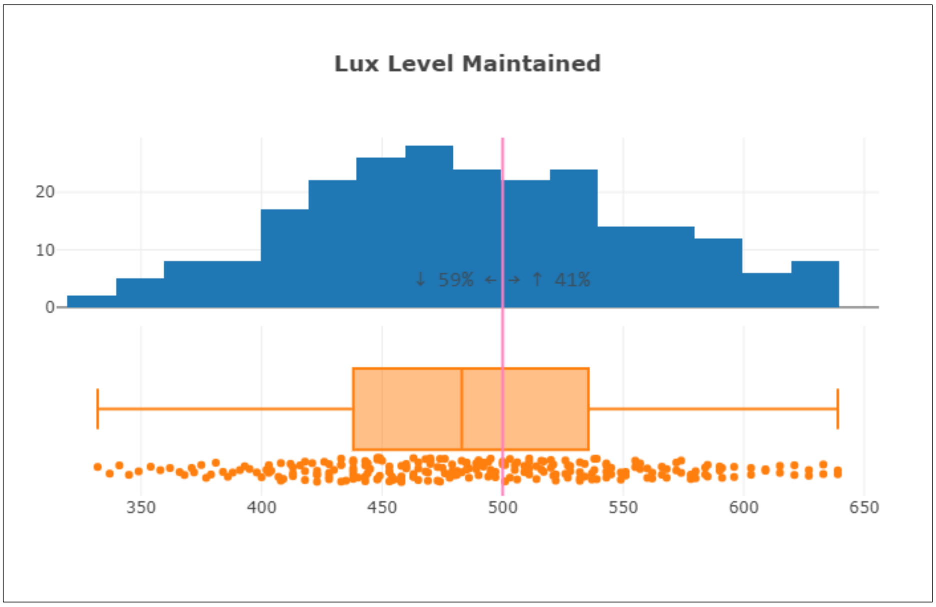


Figure 4.19 : Luminaire 3 Lux level maintenance histogram (59% of the time light levels are below 500)

4.3.1.6 Dimmable vs Non-dimmable luminaire evaluation

Two luminaires of the same wattage and luminous flux were compared using the developed tool to analyse energy efficiency and financial benefits. One luminaire was considered dimmable and the other one non-dimmable. All other luminaire and environmental conditions remained same.

Table 4.16 : Summary of results - dimmable vs non-dimmable luminaire

	Luminaire 1 Non dimmable	Luminaire 2 Dimmable
Wattage (W)	33	33
Dimmable	No	No
Lumens (Lm)	3600	3600
Efficacy (Lm/W)	109	109
UF	0.98	0.98
Lifetime (Hours)	50000	50000
Power factor	0.9	0.9

IP Rating	IP20	IP20
LLMF	0.75	0.75
MF	0.55	0.55
Lighting design		
Maintained illumination	485	500
Max. illumination	881	500
Min. illumination	501	500
Number of luminaires	64	64
Cost analysis		
Energy cost	2,302,080	1,746,863
Energy analysis		
Energy consumption (kWh)	105,600	80,128
Design LPD	8.5	8.5
Actual LPD	8.25	8.25
Percentage LPD Variation	3%	3%

When using the non-dimmable luminaire, theoretically, light levels follow the pattern of maintenance factor, while the wattage of the luminaire remains constant over years.

When using the dimmable luminaire, theoretically, wattage of the luminaire should follow the pattern of maintenance factor, while the illuminance remains constant.

Sample calculation at year 15 is done below. In the year 15, MF = 0.596. This is shown in Figure 4.21 : Maintenance factor at n=15.

Using Equation 3.14,

$$\text{Required Lumens } (F_r) = \frac{E \times A}{N \times MF \times UF}$$

$$= \frac{500 \times 16 \times 16}{64 \times 0.596 \times 0.98}$$

$$= 3424 \text{ lumens}$$

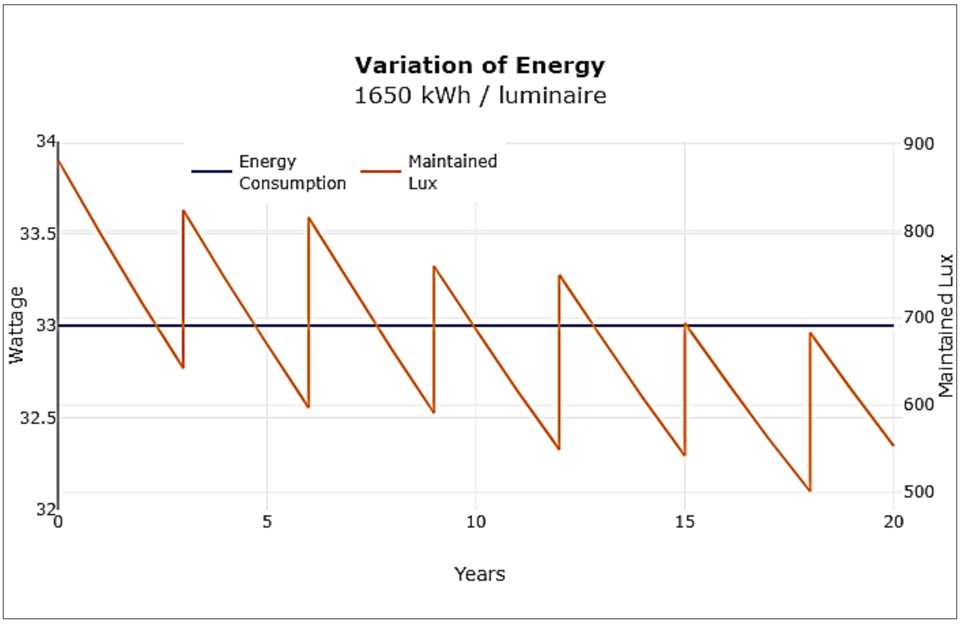


Figure 4.20 : Non-Dimmable luminaire energy consumption and maintained illumination pattern during 20years

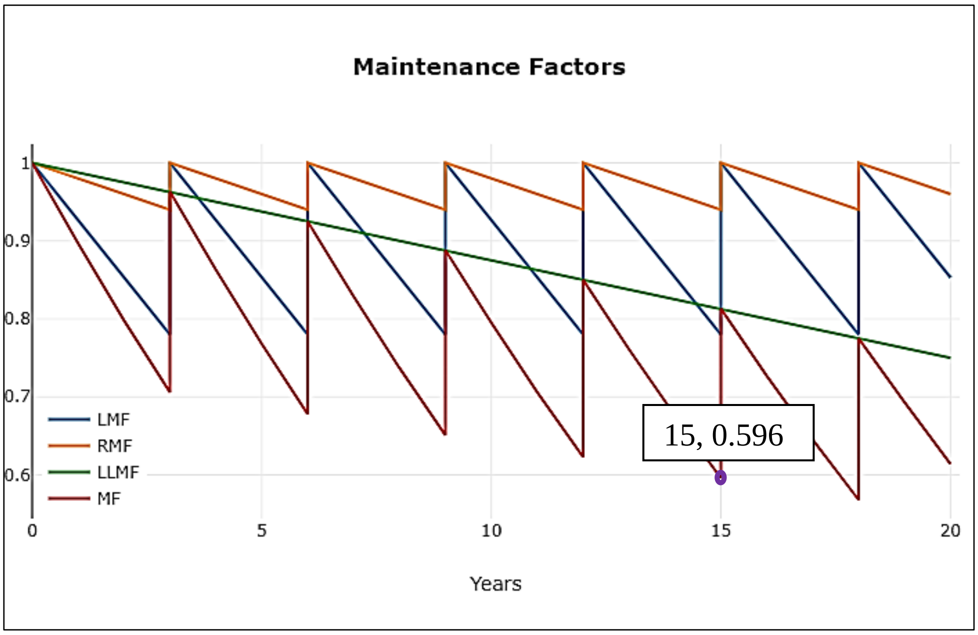


Figure 4.21 : Maintenance factor at n=15

Using Equation 3.15,

$$\text{Required Wattage } (W_r) = \frac{F_r}{\eta}$$

$$= \frac{3424}{109}$$

$$= 31.4 \text{ W}$$

This required wattage is shown in Figure 4.22 : Luminaire wattage at n=15.

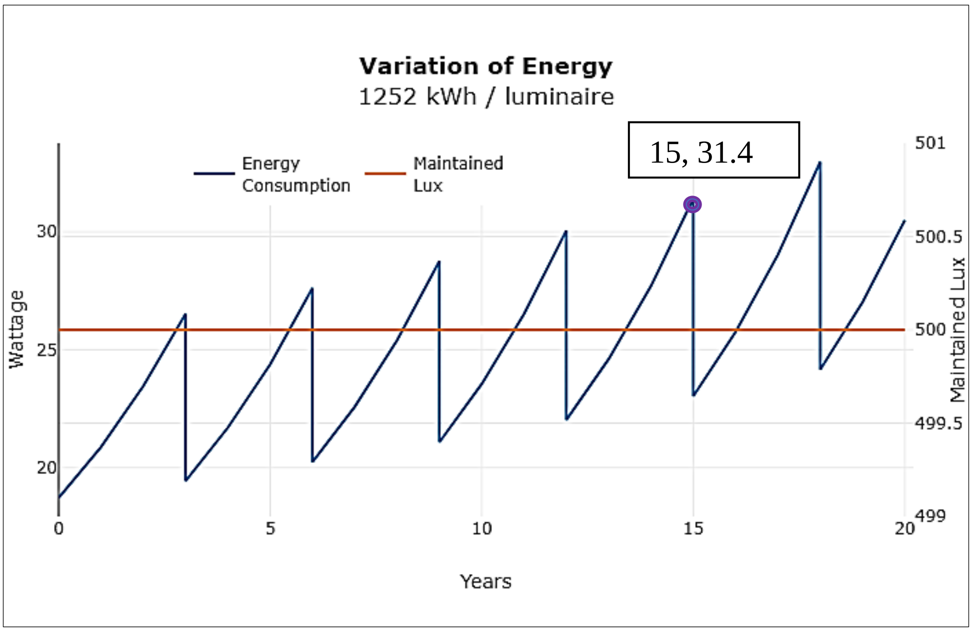


Figure 4.22 : Luminaire wattage at n=15

Energy consumption for

Non -Dimmable luminaire energy consumption for 20years = 1650 kWh/luminaire

Dimmable luminaire energy consumption for 20years = 1252 kWh/luminaire

Difference in energy consumption for 20years = 398 kWh/luminaire

Total difference in energy consumption for 20years = 398 kWh/luminaire × 64luminaires

= 25,472 kWh

Energy cost savings for 20years = 398 kWh* 21.8 Rs/kWh

= 8676.4 Rs/luminaire

Total energy cost saving for 20year period = 8676.4 Rs/luminaire×64luminaires

= 555,289.60 Rs

Average yearly savings per luminaire = 555,289.60 Rs /20 years /64 luminaires

= 433.82 Rs/year/luminaire

CHAPTER 5

5 DISCUSSION AND CONCLUSION

5.1 Discussion

Usage of LED based luminaires are continuously increasing, especially in large scale commercial buildings. Therefor it is essential to investigate thoroughly about this new technology and establish proper guidelines to select the most energy efficient and economical luminaires for a given application.

It was understood that efficacy, lifetime, CRI, power factor and IP rating were the factors affecting the price of an LED luminaire. From the sample datasheets selected for the office space, CRI was above 80 for all the fittings and the power factor was above 0.9. The requirement for maintaining an appropriate CRI value based on the application and maintaining a higher power factor close to unity for reducing the maximum demand are well understood by most of the designers as well. Maintaining an efficacy in the range of 90 -100 lumens/watt is also commonly practiced for commercial LED luminaires. What is less understood is how LED lifetime differs from other types of light sources and how to relate this lifetime into a lighting design and evaluation of different LED products.

Minimum efficacy required to comply with ASHRAE 90.1 LPD values were obtained for different types of buildings under two different LLMF values. LLMF value of 0.7 is the de facto value and it is based on the definition of the lifetime of an LED. But this value led to very high efficacy requirement with the building code compliance for LPD values. In contrast, a value of 0.9 resulted in average efficacy requirement where higher light levels were recommended and very low efficacy values for requirements where lower light levels are recommended. Therefor three interpretations of LLMF values were used for the study. However, from this relationship between the efficacy and LPD it was understood that not all buildings require the same efficacy requirement for a luminaire for building code compliance.

It was realised that when using a general thumb rule approach to maintenance factor of 0.8, maintained light levels tend to be lower than the desired light level 50%, 73% and 59% of the installation time for Luminaire 1, Luminaire 2 and Luminaire 3 respectively. Therefore, this approach is flawed and is not recommended. Using a general LLMF 0.7 value presented more accurate results but for a luminaire with higher performance as Luminaire 1 which could maintain 75% light output at its end of life, using 0.7 resulted in over illumination and over energy consumption by 12%. Deriving the LLMF based on mean design lifetime presented highest maintenance factor and obviously the lowest energy consumption. Energy consumption was reduced by 13%, 20% and 21% respectively. However, the light levels were also reduced by 10%, 11% and 7% respectively. The base case values were the ones calculated form the LLMF calculate in method 1, which the LLMF was derived using the end of life light percentage and design lifetime.

A method to calculate the energy savings from dimming the extra illumination incurred by the maintenance factor was introduced. It was observed that 24% energy savings were possible with dimming. However, to evaluate this financially, a price comparison between the two types of luminaire is essential.

The cost analysis was done for the total design lifetime. By observing the results, it was understood that from thee three components; initial cost, maintenance cost and energy cost, the highest percentage was imposed by the energy cost. This value was in the range of 63% to 81%. Therefore, it was obvious that the buying decision should not be limited by the initial cost and a total lifetime cost analysis should be done before choosing the lighting solution. Ironically, the luminaire with lowest initial cost demonstrated the highest lifetime cost.

5.2 Limitations of the study

There was no database for LED luminaires currently used in Sri Lanka at the time of study. Therefore, the total range of luminaires with different characteristics could not be discussed.

Performance of the designed lighting system highly depends on the accurate luminaire data obtained from the manufacturer. For this validating the content of the datasheets with the test certificates is essential. However, this was not done as a part of this study due to unavailability of test certificates in manufacturers' websites.

5.3 Criteria for evaluating LED luminaire-based lighting

Based on the results obtained, the important considerations of lighting design using LED luminaires were identified. To take all the necessary inputs into the design and yield meaningful results, general criteria was developed. The used criteria are shown in Figure 5.1 : Criteria for evaluating LED luminaire-based lighting.

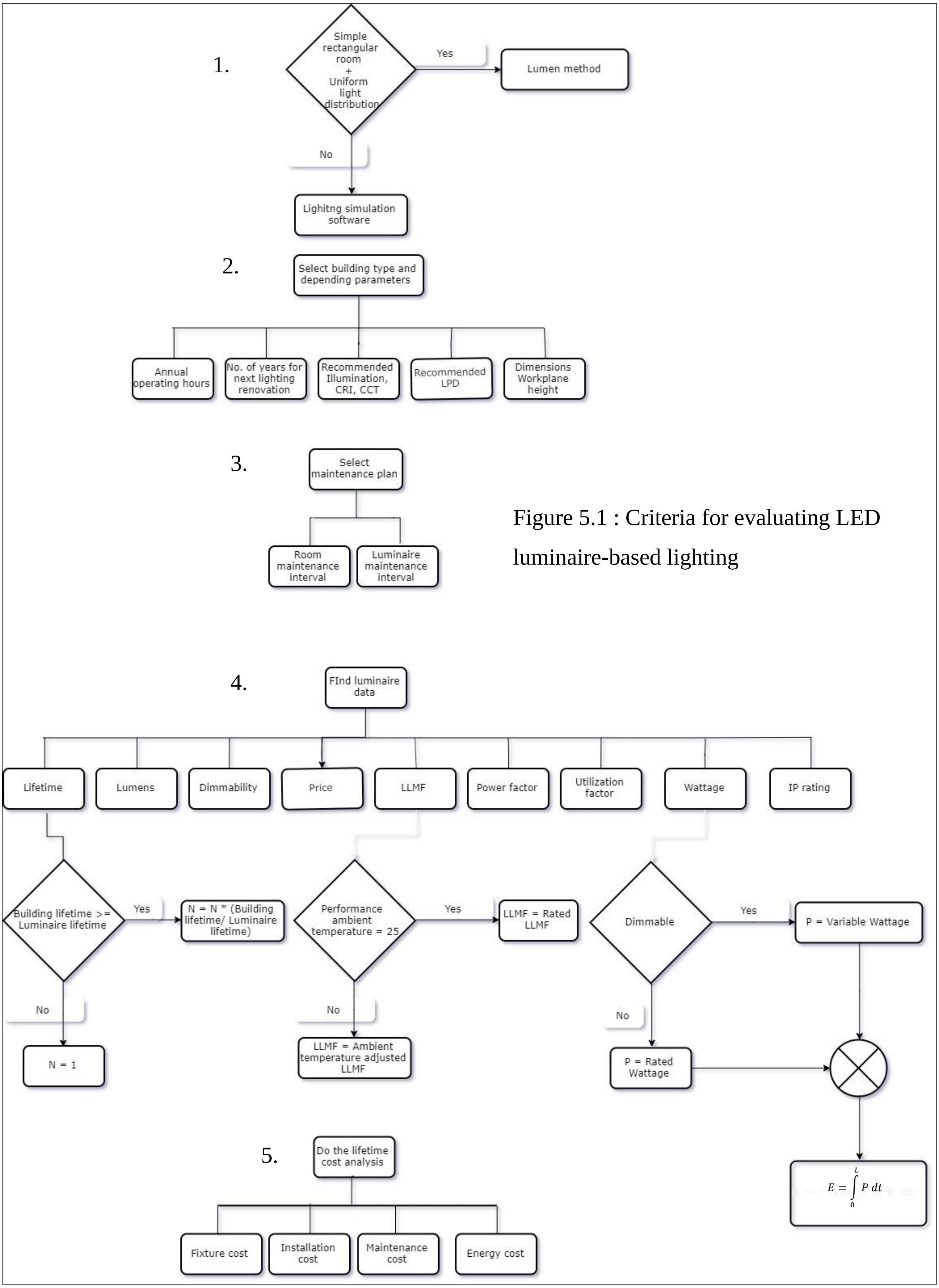


Figure 5.1 : Criteria for evaluating LED luminaire-based lighting

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