

Guidance Note 11/20

Maintenance factor determination and its impacts on the performance and overall efficiency of LED luminaires



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Executive summary

Maintenance factors are applied to luminaire photometric data to ensure that at the end of a scheme's design life, in the worst-case scenario, the specified lighting level is still maintained. The maintenance factor applied for a luminaire should reflect how the light output reduces over time due to a variety of factors including lumen depreciation of the light source and the build-up of dirt on a luminaire. BS 5489-1:2013 Annex C has long provided the recommended method for calculating maintenance factors in the UK.

BS EN 62717 and BS EN 62722 include methods for assessing LED module and luminaire performance respectively. These introduce an assessment of the expected spread of the lumen depreciation using the term L_x, B_y , measured over a test period of up to 6,000 hours using the IES LM-80 testing method. There has been some confusion in the industry about the definition and use of the B_y figure and whether it should be used as part of the LED luminaire maintenance factors.

BS PD ISO/CIE TS 22012:2019 Light and lighting. Maintenance factor determination. Way of working (referred to here as TS 22012) is the latest best practice guidance on the determination of maintenance factors, and provides much needed clarity on the methods of calculation; the reader is recommended to read that document in detail for further

guidance. TS 22012 recognises the weaknesses of the guidance in BS EN 62717/62722 relating to the L_x, B_y parameter and provides a slightly revised parameter for determining maintenance factors L_x and B_y making it clear that the median useful life, $L_x B_{50}$ should be used for determining maintenance factors.

Maintenance factors have an impact on the apparent efficiency of luminaires in a lighting scheme and particularly if assumptions are not applied consistently across all parameters. To ensure performance is as expected, the overall maintenance factor should be matched with the constant light output (CLO) factor to ensure that light levels are maintained at or above the required minimums and that power consumption at any time during the life of the product is sufficient to achieve the light levels.

Finally, a single universal parameter for overall efficiency is proposed here for inclusion in tender specifications. This parameter allows direct comparison of the overall efficiency of different manufacturers' luminaires at the end of scheme life including the effects of TM-21¹ expected lumen depreciation, applied maintenance factors and the impact of constant light output on power consumption. This parameter bridges the gap between lighting standards, CLO and power consumption over life, improving the reliability of luminaire performance comparisons.

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¹ IES TM-21-11, *Projecting Long Term Lumen Maintenance of LED Light Sources*

Review of Standards relating to maintenance factors

Introduction

This section explains how the relevant sections of BS 5489-1 and BS EN 62717² affect maintenance factors. It sets out the methods to be used for luminaire photometric data and power consumption figures which together ensure manufacturers can publish, and lighting designers can compare, the performances and energy efficiency of different luminaires on a lighting scheme.

BS 5489-1:2013

BS 5489-1 Annex C gives informative guidance for calculating the overall maintenance factor (OMF) as follows:

$$\text{OMF} = \text{LLMF} \times \text{LSF} \times \text{LMF}$$

where

LLMF is lamp [or LED] lumen maintenance factor representing the proportion of initial light output remaining at the median useful life;

LSF is lamp [or LED] survival factor representing the proportion of LEDs in a luminaire that are expected to remain working at the median useful life;

LMF is luminaire maintenance factor representing the dirt build-up and

other deterioration of the optic surfaces/materials as BS 5489-1: 2013 Annex B, Table B1.

The proportion of luminaires that are no longer producing any light is ignored in the LSF assessment as it is expected that these luminaires will be maintained before assessing the lighting levels.

LLMF is calculated using IES LM-80 LED depreciation testing with extrapolation out to 5.5 or 6 times the test period using IES TM-21³.

An ISTMT (in-situ temperature measurement test) of the LED nominal case temperature shall be completed with the complete luminaire operating in the ambient air temperature⁴. The measured LED case temperature allows the correct curve to be selected on the TM-21 chart. If the LED case temperature falls between two temperature curves in TM-21 graphs, interpolation may be used, or alternatively the higher temperature curve can be used conservatively. Then the burning hours of the luminaire can be correlated to the normalised light output to identify the light output depreciation over time.

Readers should note that the test methods in IES LM-80 provide best case results for LED lumen depreciation under the defined operating conditions. Temperatures and drive currents are held accurately at

IMPORTANT: For tenders and lighting scheme comparisons where BS 5489-1 is specified, the overall maintenance factor for each luminaire make and model should be determined separately using manufacturers' published LLMF and LSF values. Specifying and using the same generic value of overall maintenance factor for all luminaires submitted under a tender would understate the performance of well-designed luminaires and overstate the performance of lower quality luminaires, skewing the results of tender assessments towards products which may fail sooner than expected.

² BS EN 62717 defines "maintained values" as being the photometric characteristic at an operational time under standard test conditions. Clause 6.1 defines the test period. Clause 10.2 states it is impractical to measure the actual lumen reduction over life and therefore refers to "lumen maintenance codes" which define the initial reduction in lumen output over the test period. Tables ZZA.1 and ZZB.1 in Annex ZZA to ZZB both confirm that lifetime and *lumen maintenance at the end of nominal life* are outside the scope of both the Eco-design Regulations and BS EN 62717.

³ LM 80 and TM 21 testing standards form the basis of all useful life calculations, and are explained in more detail in Appendix A.

⁴ In the UK, ambient air temperature of 25°C is used unless specified otherwise.

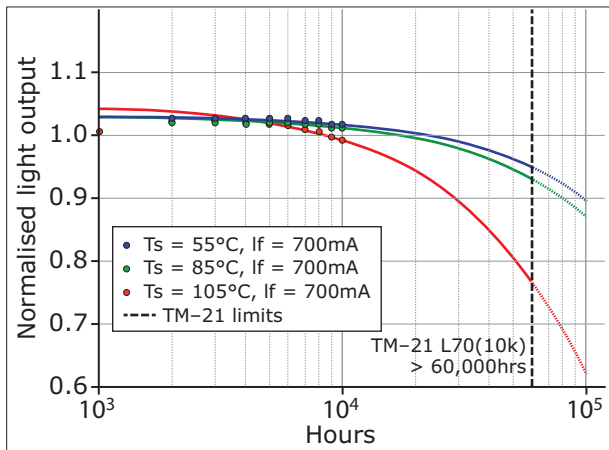


Figure 1: Typical TM-21 graphs

consistent values without spikes or variations, humidity is controlled, and no chemical contamination or air pollution is present. The tests also exclude any effects of switching cycles on the LED performance or life. Switching cycles may have a life limiting effect on the LED module and LED driver.

LSF is impractical and uneconomic to determine accurately due to the time required for testing a statistically significant population of luminaires to end of life. LSF = 0.98 or LSF = 0.97 are common but these figures are typically estimated by LED component suppliers using statistical methods. LSF of 0.97 representing 3% failures of individual LEDs in a working luminaire shall be used unless evidence is provided by the LED supplier or luminaire manufacturer to show an alternative value of LSF is appropriate. The 3% has been selected arbitrarily as representing values typically used by manufacturers in the industry. It provides a consistent benchmark that avoids results being skewed by under-estimating or

5 Possible LED PCB architectures and the impacts of LED failures resulting from these are discussed in Appendix E.

6 This standard is published as a voluntary method of establishing a presumption of compliance with the eco-design requirements of:
Commission Regulation (EC) No. 244/2009 (see BS EN 62717 Annex ZZA) for Non-directional Household Lamps
Commission Regulation (EC) No 1194/2012 (see BS EN 62722 Annex ZZB) for Directional Lamps, LED Lamps and related equipment
Commission Delegated Regulation (EU) No 874/2012 (see BS EN 62717 Annex ZZC) for Energy Labelling of Electrical Lamps and Luminaires.

ignoring parameters in the maintenance factor calculation that are not able to be calculated accurately.

It is clear that the architecture of the LED, the LED package, the circuit arrangement on the LED board, the driver type and method, the number of switching cycles, the power supply quality and the probability of being struck by lightning etc will all have an effect on the actual useful life of the LED products⁵. The median useful life based solely on TM-21 extrapolations of lumen depreciation is likely to overstate the life of the luminaire by omitting these effects. However, TM-21 is currently the best available and most commonly used method for projecting long term lumen maintenance of LED light sources.

Luminaire maintenance factor, covering dirt build-up and cleaning cycles, should be chosen in accordance with BS 5489-1:2013 Annex B. The original research on which the dirt build-up figures was based used HID luminaires but they are expected to be representative for LED luminaires until the research is repeated with LED luminaires.

BS EN 62717 LED lamps and LED modules⁶

The publication of BS EN 62717 *LED modules for general lighting* is used to define the performance of LED modules by carrying out tests and considering the change in performance of the luminaire between the start and end of the test.

While BS EN 62717 relates only to LED modules, it is directly aligned with BS EN 62722-1 *Luminaire Performance* and the definitions for L_x are used throughout to represent performance at the end of the 6,000 hour test period.

Clause 10.2 discusses lumen maintenance over the test period and defines a code to represent the luminaire performance based on the testing period. Notes 1 to 4 should be referred to for the limitations of the guidance provided. Note 1 recognises that it is impractical to measure the lumen

reduction over the life of the LED module and recommends that the testing is carried out up to 25% of the rated life of the luminaire, to a maximum of 6,000 hours (see also BS EN 62717 clause 6.1). For luminaires with more than 24,000 hours rated life, this defines the test time as 6,000 hours.

Defining the maintained light level, L_x , in BS EN 62717 as the maintained flux at the end of the 6,000-hour test period creates confusions because BS 5489-1 refers to the maintained light levels at the end of the useful life of the luminaire. As such the L_x parameters as defined in BS EN 62717 are not suitable for use in determining the maintenance factor of luminaires.

BS EN 62717 Annex A sets out normative guidance on the use of IES LM-80 (see page 4 above) for lumen maintenance, but again this only considers the maintained lumen output at the end of a test of a single LED.

Annex C introduces B_y in the term L_x, B_y giving a representation of the tightness or spread of light output levels across a population of LED modules⁷. B_y defines the proportion, y (in %), of the population of LEDs that has fallen below the threshold light output L_x where x is the remaining percentage of the initial light output. L_x, B_{50} defines the median useful life as the time taken for 50% of the population of LEDs of the same type to have fallen below the lumen maintenance defined by L_x . The spread of light output levels can be illustrated as a bell curve (normal distribution) of maintained light output levels of a population of LEDs or LED modules at the stated time. Unfortunately, this provides only informative explanations of LED product full lifetime metrics as no standardised methods of calculating or testing the parameters are offered, and so claimed performance of different manufacturers' products might vary and therefore may not be comparable. Also, the life of the LED modules given in the example is typically indicating a rated life

of 10,000 to 30,000 hours and no suggestion is made that this would adequately predict the performance at 50,000 hours or 100,000 hours.

The methods set out in BS EN 62717 do not suggest L_x, B_y represents the performance of the luminaire at the end of the scheme life, and so the L_x, B_y figures should not be used for calculated maintenance factors. For the same reason L_x, B_{10} should not be used by customers to specify the minimum performance at the end of the rated life or by manufacturers to make claims of luminaire performance at the end of the rated life. These figures are typically given as marketing material and are not based on evidence of lifetime testing.

When to use L_x, B_{50} and L_x, B_{10}

In cases where LED optical distributions are using 'overlay' optics and all LEDs in the module are lighting the same area, for example street lighting or area flood lighting, the use of L_x, B_{50} , the median useful life from IES TM-21, is sufficient and significantly simplifies the calculation of maintenance factors. Note: the validity of the prediction is limited to 5.5 or 6 times the test duration, and so any extrapolation from TM-21 graphs beyond that limit should be treated as indicative rather than claimed performance.

Where each LED or group of LEDs is illuminating a different section of the lit object, for example linear luminaires providing wall washing, any difference in illuminance level would be obvious and would detract from the artistic effect. In these cases, the distribution of lumen depreciation across the products supplied will need to be more tightly controlled and the customer may specify the luminaires using L_x, B_{10} to prevent a visible shift of the light colour across the wall. That said, the light levels required at the end of the useful life of the installation should still be calculated based on L_x, B_{50} for the median useful life.

Note that there are some unexpected consequences from specifying tighter

⁷ See Appendix B regarding uncertainties related to using B_y .

lumen depreciation spreads as L_x, B_{10} . (See also Appendix B.)

First, the 'rated life' of different LED modules (and so luminaires) will be affected by the number of individual LED dies used, assuming that each LED fails independently. Statistically, increasing the number of LED chips reduces the impact of any one LED die failing, so providing more LED chips in a luminaire artificially increases the rated life. This makes it impractical to compare schemes where maintenance factors are calculated at anything other than L_x at the median useful life and suggests L_x, B_{10} should not be used for calculating maintenance factors for lighting schemes.

Second, lighting schemes are based on the average light levels over a defined area. If the expected useful life of a lighting design was specified in terms of the L_x, B_{10} rated life, the average light levels on the lit surface at the point where this luminaire reaches L_x, B_{10} end of life are likely to be greater than the average lighting levels required by the lighting design specification. This creates uncertainty when comparing lighting survey results to the lighting specification to decide if the scheme is still compliant or if it needs to be replaced.

In addition to parametric failure, BS EN 62717 introduces other definitions that relate to the performance at the end of the testing period. These include abrupt failure probabilities and values⁸ and the time to abrupt failure, C_y ; the combined failure value at the median useful life and, for LED lamps only, $M_x F_y$ which combines the parametric and abrupt failure modes. Note: $M_x F_y$ is not relevant for LED luminaires or LED modules in luminaires where replacement LED lamps are not used. More detail is provided in BS EN 62717 for these definitions.

BS EN 62722-2-1 LED luminaires

The L_x, B_y rated life for a luminaire to BS EN 62722 is defined by testing either the LED module or the full luminaire to the requirements of BS EN 62717. BS EN 62722-2-1 makes provision to check the module temperature limit, t_p , when installed in the luminaire operating at the luminaire ambient temperature limit, t_q . Again these values all relate to the maintained performance at the end of the test period, defined as the minimum of 25% of the rated life up to a maximum of 6,000 hours.

For exterior lighting applications where life claims may be 50,000 hours or above, BS EN 62722-2-1 does not offer a suitable maintenance factor calculation method.

BS PD ISO/CIE TS 22012:2019 *Light and lighting – Maintenance factor determination – Way of working*

At the time of writing, this Published Document BS PD ISO/CIE TS 22012:2019 (referred to here as TS 22012) is relatively unknown, and part of the aim of this ILP Guidance Note is to draw attention to the guidance and approaches presented in TS 22012.

TS 22012 updates best practice in determining maintenance factors to specifically consider LED luminaires. In doing so it reuses much of the methodology in BS 5489-1 but, for clarity and to avoid confusion, it defines new symbols for those parameters as well as adding new parameters required for LED technology.

The overall maintenance factor from BS 5489-1 is renamed simply maintenance factor, f_m

$$f_m = f_{LF} \cdot f_S \cdot f_{LM} \cdot f_{SM}$$

where

f_{LF} is the luminous flux factor (equivalent to LLMF);

⁸ Abrupt failures of LED luminaires are covered in Appendix C.

- f_S is the survival factor (equivalent to LSF);
- f_{LM} is the luminaire maintenance factor (equivalent to LMF);
- f_{SM} is the surface maintenance factor (interior luminaires only, use 1.00 for exterior luminaires).

The publication of TS 22012 supersedes the method in BS 5489-1 as well as being a replacement of the methodology as described in CIE 097:2005 and CIE 154:2003.

The approach taken in TS 22012 applies to both interior and exterior lighting products. Parameters like the surface maintenance factor, f_{SM} are not relevant to outdoor lighting designs.

TS 22012 identifies that the setting of constant light output (CLO) parameters in the LED drivers or central management systems can impact on the energy consumption and light output of the luminaire over time and recognises that there is a direct link between the maintenance factor, f_m and the CLO setting – that is, for $f_m = 0.80$ the driver CLO percentage should be set to 0.80 or 80%.

As the luminaire expected working life is typically greater than the test periods of 6,000 hours used in BS EN 62717, the requirements and method set out in BS 5489-1 shall be followed for calculating the maintained light levels in lighting designs for exterior lighting.

Selecting a luminaire using system efficacy

System level luminaire comparison

Outline

Choosing a luminaire is commonly based on the combination of price and efficiency. While price is easily compared, the

performance and efficiency data published across the industry is not standardised and so not easily compared. Direct comparison of the initial lumen output and initial power consumption giving the initial luminous efficacy is unreliable because it ignores the light level, and with CLO the power consumption changes over the life of the luminaire. A better performance comparison method is to look at different luminaires completing the same lighting task. This can be further improved by making the energy and light output comparison at luminaire system level for the full life of the scheme including the maintenance factors.

To do this, select a representative lighting scheme arrangement that can be lit to the same lighting class by the range of luminaires being compared. Selecting and fixing typical column spacings and heights and selecting realistic lighting levels for the task ensures a fair and appropriate comparison.

Calculate the specific maintenance factor for each luminaire individually based on the manufacturer's published data. Using the same maintenance factor for all luminaires may introduce a bias towards lower quality LEDs that is likely to lead to selection of products that have other problems relating to production quality and limited life.

Allowing variation of parameters that can reasonably be adjusted to suit the luminaire (for example luminaire tilt, optical distribution, light output level), the lighting design can be optimised to give the correct initial luminous flux required to achieve the maintained light levels at the end of the scheme life.

The total power consumption for each luminaire over life (allowing for constant light output functions where applied) can then be compared to see which is the most energy-efficient solution to complete the task.

Maintained luminous flux

This comparison requires the published photometric files output, which typically

represents the initial luminaire output, to be adjusted using the appropriate maintenance factors for each luminaire. This sounds like a trivial step, except that the application of luminaire maintenance factors is not consistent across the luminaire manufacturers. The following approaches are possible although these are not all recommended:

- photometric files with end-of-life luminous flux where maintenance factors are included for lumen depreciation and LED failure;
- photometric files with initial luminous flux where manufacturers publish the maintenance factors to be used in the design;
- photometric files with initial luminous flux and a generic maintenance factor applied;
- photometric files with initial luminous flux and no maintenance factors applied.

In accordance with BS 5489-1 and BS PD CIE/ISO TS 22012, it is recommended that manufacturers issue the absolute photometric files representing the initial light output of the luminaire and publish a table of maintenance factors that represents the luminous flux factor and survival factor over the life of the scheme. These may be presented for a range of drive currents or may be presented for the worst-case drive current. Together with the luminaire maintenance factor this information defines the light output of the luminaire at the end of the scheme life⁹.

⁹ Where the luminaires have different expected lifetimes, some of which are below the expected scheme life, the lowest common multiple life should be selected as the comparison period, and the total cost of ownership figures should be calculated for this period. For example, with lifetimes of luminaire A of 12 years and luminaire B of 24 years, the scheme life of 24 years, the comparison should be based on the capital cost of purchasing two luminaire A (covering 0-12 years and 12-24 years) and one luminaire B (covering 0-24 years) plus the total energy consumption figures for each luminaire for the full 24 years (24 being the lowest common multiple of 12 and 24).

¹⁰ LED manufacturers' application process can be found by searching the Elexon website. The section titled "What about Constant Light Output (CLO)?" is referred.

Lifetime power consumption

The luminaire power consumption can be determined over the expected life, with or without CLO applied. The power consumption figures can generally be taken from the Elexon UMS charge codes. Some assistance may be required correlating the charge codes with the luminaire's configuration selected.

Constant light output

The use of constant light output (CLO) features that compensate for the maintenance factor can help to reduce the power consumption of a luminaire over its life. Where CLO is applied, manufacturers must use a linear power increase over time to ensure the power consumption is accurately represented by the mid-life power consumption, as stated in the Elexon guidance for manufacturers¹⁰. The use of non-linear power increase will result in the mid-life power being not equal to the average power over life and power consumption will be misrepresented.

Another area where figures can be misused is in the correlation between the maintenance factors applied to the luminaire and the CLO figures applied to the LED driver. The intention of CLO is to increase power to compensate for the lumen depreciation over the life of the luminaire. In that case, the CLO factor applied in the LED driver should be equal to the maintenance factor expressed as a percentage; for example $f_m = 0.80$ would give a CLO factor of 80%, and the power consumption over the life of the scheme should be based on this CLO factor. It is recommended that this requirement is explicitly specified in the tender specification.

LED performance figures

To compare the overall efficiency of the luminaires, use the published photometric files and maintenance factor for each luminaire to find the minimum LED drive current required to meet the lighting level specification. Then calculate the power consumption typically using the Elexon

unmetered supply charge codes to represent the accurate power consumption used over life. Where CLO is applied and the initial power consumption figures are provided, the total energy consumption is given as:

$$E = P_{\text{initial}} \cdot \frac{[1 + (\text{CLO}\%/100)]}{2} \cdot T_{\text{scheme}}$$

where

E is the energy consumption over the scheme life in watt-hours

P_{initial} is the initial power consumption when the luminaire is installed in watts

$\text{CLO}\%$ is the CLO factor expressed as a percentage

T_{scheme} is the burning hours expected during the scheme life in hours.

Where CLO is applied and the power consumption figures for the luminaire at the end of scheme life are provided, the total energy consumption over the scheme life is given as:

$$E = P_{\text{End}} \cdot \frac{[1 + (\text{CLO}\%/100)]}{2} \cdot T_{\text{scheme}}$$

where

E is the energy consumption over the scheme life in watt-hours

P_{end} is the power consumption at the end of scheme life in watts

$\text{CLO}\%$ is the CLO factor expressed as a percentage

T_{scheme} is the burning hours expected during the scheme life in hours.

If the CLO power consumption is given directly the power consumption over the scheme life is:

$$E = P_{\text{CLO}} \cdot T_{\text{scheme}}$$

where

E is the energy consumption over the scheme life in watt-hours

P_{CLO} is the CLO power consumption in watts

T_{scheme} is the burning hours expected during the scheme life in hours.

LED circuit architecture

The effects of the circuit architecture shall be taken into account when defining the final LSF figure, recognising that a single LED failure may result in adverse drive current distribution resulting in sequential failure of additional LEDs or in the worst case the whole circuit of LEDs failing.

Testing tolerances

Luminaire manufacturers are beginning to publish tolerances on the claimed light output based on the spread of performance across the LED flux bin (for example $\pm 7\%$) and on the power consumption measurements (for example $\pm 11\%$). These tolerances may be based on the size of the flux bins and voltage bins defining the LED performance or can be related to the accuracy and uncertainties involved in the photometric measurement of the LED luminaire by an ISO 17025 laboratory.

These tolerances have a significant effect on the system efficiency depending on whether the lower values, nominal values or highest values of light output and power consumption are combined. To give a conservative comparison avoiding further manipulation of figures, the minimum flux tolerance and maximum power tolerance should be compared. However, these figures would be unrepresentative of the overall efficiency results of the luminaire. It is recommended that nominal figures excluding tolerances are stated but that the upper and lower bounds of luminous flux and power consumption tolerance are also clearly stated.

A word on published LED efficiency claims

The headline LED efficiency figures in brochures and datasheets and the methods for calculating these vary dramatically from manufacturer to manufacturer. These figures are not necessarily a reliable method to compare or select luminaires for commercial tenders. These figures can be manipulated, for example, by comparing

the initial LED module flux (excluding optical losses and depreciation over life) and comparing it with initial LED power consumption (reduced by the CLO factor). Figures that appear to be more than 150lm/W are almost certainly not representative of the real world energy consumption over the life of the product. Care should be taken during the preparation of tender specifications and comparisons of tender responses to determine if such figures are reasonable, and evidence of the calculations and testing behind the numbers should be requested if in doubt; see Appendix D.

In an attempt to provide a representative and fair comparison between different products from different manufacturers, an overall efficiency parameter is proposed. The overall efficiency can be specified in the tender documents requiring each manufacturer to claim this to give a standard assessment process.

Overall efficiency

To make it easier for customers and purchasers to compare luminaires using datasheets, the Institution of Lighting Professionals is asking luminaire manufacturers to publish, and purchasers to specify publication in their contracts, a single standard comparison efficiency figure for each luminaire model that we will call the overall efficiency.

The overall efficiency shall be the maintained luminous flux divided by the average CLO power consumption of the complete luminaire determined as follows:

1. the maintained luminous flux and average CLO power consumption of the luminaire measured with the luminaire drive current greater than or equal to 700mA to each high-power LED or 100mA drive current to each mid-power LED regardless of the circuit architecture being series, parallel, ladder, or series parallel.
2. Maintained luminaire flux shall be measured using the following procedure:

- a. Initial luminous flux of the complete luminaire (including optics and any diffuser, bowl or glass front) shall be measured on a goniophotometer or an integrating sphere with the drive current set at the designated nominal value and the CLO factor set at 100% representing the end-of-life power consumption condition.
 - b. Testing shall be completed at ambient air temperature, $T_a = 25^\circ\text{C}$.
 - c. The initial luminous flux multiplied by the BS 5489-1 (LLMF \times LSF) elements of the maintenance factor to give the maintained luminous flux at end of life.
 - d. LLMF based on IES TM-21 prediction using the nearest higher temperature curve to the LED reference (solder point or junction) temperature taken from the in-situ temperature measurement test at ambient air temperature, $T_a=25^\circ\text{C}$.
 - e. LSF taking account of both the number of LED failures expected during the life of the luminaire (use actual figures where available but no less than the greater of 3% of LEDs or one LED failure per LED module).
 - f. The effects of the LED module circuit architecture taken into account when assessing the impact of a single LED failure on the performance of a luminaire. This may result in adverse drive current distribution around the circuit, leading to sequential failure of further LEDs or in the worst case, the whole circuit board going out of light.
3. The average CLO power consumption of the complete luminaire using the Elexon guidance on determining the CLO power, using a straight-line power increase between the initial power and end-of-life power, including driver losses.

The overall efficiency will allow the typical performance of two luminaires to be compared including all relevant factors including initial LED flux, LED lumen depreciation, LED survival rates, thermal management and optical efficiency.

Conclusions

Maintenance Factors methods in BS 5489-1 are relevant for HID luminaires and should be calculated using the methods in BS 5489-1.

The methodology in BS PD ISO/CIE TS 22012: 2019 is the best practice approach for calculation of maintenance factors for LED luminaires.

The guidance in BS EN 62717 and BS EN 62722 is not suitable for the calculation of maintenance factors for any luminaires.

L_x, B_y should not be specified for the performance over the rated life of a luminaire as the methods in BS EN 62717 and BS EN 62722 relate to the performance at the end of the test period not the end of the rated luminaire life. The median useful life, L_x, B_{50} shall be used for calculating maintenance factors.

A standard method is presented for calculating the overall efficiency of the luminaire. This method outlines a testing and calculation method using standardised methods and co-ordinated operating parameters to ensure performance and overall efficiency claims for luminaires are reliable.

Appendices

- A. LED standards
- B. Uncertainties in useful life predictions
- C. Abrupt failure
- D. Luminaire manufacturers performance data
- E. LED failure modes and consequences

Appendix A – LED standards

It is important that the designer understands the LED standards and the possible impact that differences in testing variables have on LED and luminaire life, and how these could impact the overall maintenance factor. Relevant standards are listed and summarised below alongside key things to watch out for.

LM-79-08, *IES Approved Method For The Electrical And Photometric Measurements Of Solid-State Lighting Products*. In brief by following this standard a manufacturer will provide the following data: Total Luminous Flux, Luminous Intensity Distribution, Electrical Power Characteristics, Calculated Luminous Efficacy and Chromaticity Characteristics.

LM-80-15, *IES Approved Method: Measuring Luminous Flux And Color Maintenance Of LED Packages, Arrays And Modules*. LM-80 applies to the LED package, array, or a single module and not a complete system, in short it is testing at component level only. The standard does not provide guidance for extrapolation of testing results, however it will provide luminous flux for a given current over at least 6,000 hours period with interval measurements. The key thing to note here is this is the starting point for all manufacturer longevity calculations in TM-21.

TM-21-11, *Projecting Long Term Lumen Maintenance of LED Light Sources*. This uses LM-80 data and makes useful LED lifetime projections. The standards apply to lifetime projection of an LED package, array, or a single module. The results from this calculation can then be used to interpolate the lifetime of an LED source within a system using the in-situ LED source case temperature to calculate overall longevity of the system. The key thing to note is that while projections are suggested to be limited to 5.5 or 6 times the available LM-80 data period, often manufacturers will extrapolate up to 14 times, so projected and reported lifetime may or not be the same. This is important to clarify up front with your prospective

manufacturer. Finally as an aside, if total LM-80 data period is between 6,000 and 10,000 hrs, the manufacturer will consider the last 5,000 hours and if total data period is above 10,000 hours, the manufacturer will use the last half of collected data.

Appendix B – Uncertainties in useful life predictions

The LM-80 testing, and therefore the TM-21 LED lumen depreciation prediction, is based on controlled test conditions which are unlikely to accurately represent the operating conditions of the LEDs in the luminaire once installed. Life predictions resulting from a parametric failure of the luminaire due to excessive lumen depreciation is likely to occur before the prediction provided by TM-21, assuming the luminaire is operating at the test parameters. This means that there is a degree of uncertainty in the test results. It is not currently known how great the effect of this uncertainty is on life predictions of the luminaire. The uncertainty may need to be assessed in future research as long-term data on lumen depreciation performance and failure modes of luminaires is available.

If considering using expected useful life figures based on acceptable failure rates other than B₅₀, care needs to be taken in moving from LED life predictions to luminaires life predictions as the number of LEDs installed in a luminaire has an impact on the life prediction figure.

Appendix C – Abrupt failure

Abrupt failure may be caused by a critical component or assembly failure causing the luminaire to no longer emit light.

As with parametric failures, for a population of luminaires we must define the proportion of luminaire abrupt failures, C_y, that is acceptable.

Abrupt failures can be caused by failures by any of the following:

- Optical components
- LEDs

- PCB assembly
- Thermal management system
- Housing
- Finish
- Gaskets
- Sealants
- Mechanical assembly
- Electrical components
- Driver
- Controls
- Wiring
- Electrical assembly

Where it is economical to replace the failed part, this maintenance may allow the useful life of the luminaire to be extended, but otherwise the luminaire will need to be replaced. This should form part of a total-cost-of-ownership consideration.

Appendix D – Luminaire manufacturer performance data

To assist lighting designers, it is recommended that manufacturers and distributors of luminaires provide the following information:

- Raw test data
 - Ambient test temperature
 - Measured temperatures of critical components
- Normalised data
 - Normalised data at specified ambient air temperature (typically 25°C)
 - Graph allowing selection of driver and LED reference temperatures (for example, T_{case} and T_j or T_s)
- LLMF
 - LM-80 data and TM-21 prediction curve of lumen depreciation at test temperatures data is available
- Driver mortality
 - Driver manufacturer's mortality curve (e.g. Life v T_{case})
- Luminaire life
 - Luminaire life curves against drive current and ambient air temperature

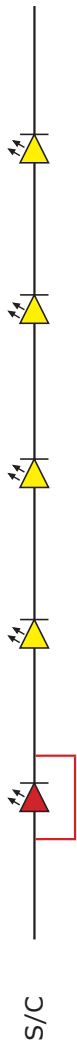
Appendix E – LED failure modes and consequences

The LED electrical failure mode (open circuit due to a solder joint or bond wire

failure or short circuit due to a LED die failure) and the LED module printed circuit board architecture (series, series parallel or ladder circuit) affect how the luminaire will behave in the event of one or more LED failures. Figure D.1 (see page 16) shows simplified circuit diagrams of the LED chains and Table D.1 (see pages 17-18) gives a description of the results from short or open circuit failures in each case.

Luminaire manufacturers should advise which failure modes can be expected for their circuit and LED type and explain the operating behaviour of the other LEDs in the circuit in the event of one, two or more LED failures. Where the failure of one LED increases the likelihood of a second LED failure through electric current redistribution (current hogging), this should be highlighted and the LED survival factor adjusted accordingly for this sequential failure mode.

One out
No change in drive current in remaining LEDs

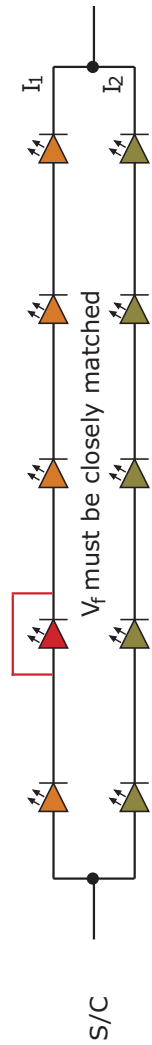


Series circuit

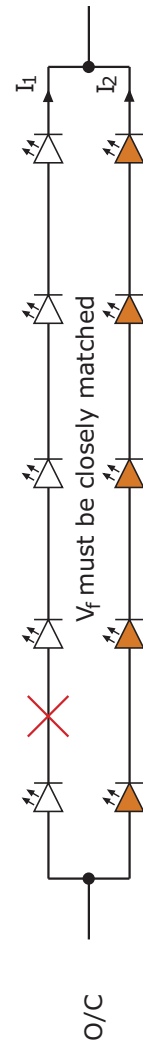
All out
Total failure



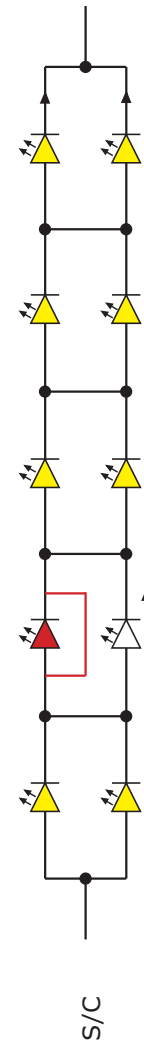
I_1 increases dramatically
 I_2 decreases dramatically



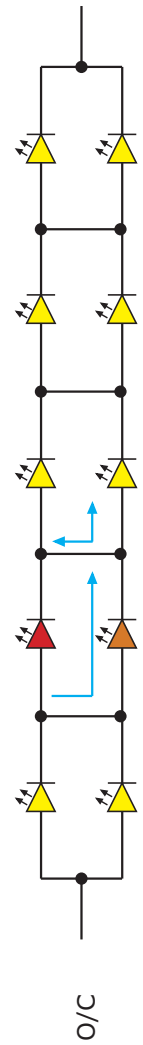
$I_1 = 0$
 $I_2 = \text{Full drive current}$



Both LEDs in ladder section go out
Rest remain at same drive current



One parallel LED gets 2x current of others



S/C = Short circuit
O/C = Open circuit

▲ Normal
▲ Failed
▲ Overpower
▲ Underpower
 Short circuit
 Open circuit

LED failure	Circuit architecture		Single LED failure – effect on...		Multiple LED failure effect	
	Series	parallel	Light output	Drive current to other LEDs		Life of remaining LEDs
Short circuit	Series		Light output reduces by flux of one LED.	No change	Improves slightly	As single LED failure.
Open circuit	Series		Luminaire fails	No current flow	Not in light	Not in light after first LED failure
Short circuit	Series parallel		Light output reduces slightly	Reduced forward voltage in chain with failed LED leads to 'current hogging' in that chain	Increased current increases T _j significantly, increases depreciation and reduces life.	Multiple LED failures more likely operating due to operation at higher drive current and junction temperature.
Open circuit	Series parallel (several long series circuits in parallel)		Light reduces slightly. No light output from LED chain with failed LED. Parallel chains increase light output but don't fully compensate due to increased junction temperature.	Drive current re-routed via working LEDs in parallel chains	Increase in drive current to parallel chain increases T _j significantly, increases depreciation and reduces life. Increase in drive current may lead to over-running LED.	Single LED failure causes chain of LEDs to be out of light. Increases risk of future failures of remaining LEDs which in turn lead to the remaining full chains failing.

LED failure	Circuit architecture		Single LED failure – effect on...		Multiple LED failure effect
	Light output	Drive current to other LEDs	Life of remaining LEDs	Life of remaining LEDs	
Short circuit	Ladder (lots of short series circuits in parallel)	Light output will reduce by the number of LEDs in the failed parallel ladder section.	Drive current to other LEDs in the same rung goes to zero and in other rungs remains unchanged	Life remains unchanged or improves slightly (reduced power in luminaire will mean the LEDs run slightly cooler)	As single LED failure.
Open circuit	Ladder (lots of short series circuits in parallel)	Light output reduces slightly. One short series chain of LEDs goes out but parallel chains increase output to compensate. Increase T_j will reduce light output.	Drive current re-routed via working LEDs in parallel chains	Small increase in drive current to parallel chains increases T_j , increases depreciation and reduces life but only slightly.	More tolerant to individual LED failures than with open circuit LEDs in series parallel. Single LED failures can occur separately. Drive current redistribution across many parallel chains has less impact on individual LEDs but as number of individual LED failures increases the consequences increase leading to sequential failure of LEDs and reduced useful life. More tolerant to individual LED failures than with open circuit LEDs in series parallel.