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ENDURANCE TEST ON PHOTOMETRIC PERFORMANCE FOR FIRST GENERATION LED LUMINAIRES

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Abstract

Manufacturers of LED luminaires promise very long lifetimes for their products. This is a main advantage compared to traditional light sources. Long operational lifetimes are particularly interesting for reducing maintenance efforts and to ensure the ecological and economical relevance of this technology. However, Light Emitting Diodes typically show a gradual depreciation of their characteristic photometric performances. The key point is thus to make sure that the luminaires still meet the expected performances after many hours of operation.

The main objective of this study is to identify the relative light output of luminaires over long running times in realistic conditions and to identify the course of the depreciation. Secondly it is intended to extend the lifetime evaluation to other indicators. The current standardized lifetime definition takes only the variation of light flux into account as a parameter. Nevertheless, complementary performance issues such as colour shift and the changes of the input power should also be considered. Just as the lumen depreciation these characteristics can also render a product gradually obsolete.

This paper addresses the results of an experimental endurance test on photometric performances and electrical parameters for a selection of luminaires of various types and price categories. It was found that the lumen depreciation shows a relative consistent path over time, while colour shift tends to show more irregular patterns and thus it is more difficult to predict. Colour shift is also much more perceptible than lumen depreciation in any typical application case so more attention should be paid to this problem. Meanwhile it was observed that the energy efficiency of the luminaires depreciates in a similar way to the loss of light output. As different causes for depreciation coexist, lifetime claims should always consider the whole luminaire system in order to determine the operational service time.

Keywords: LED luminaires, lumen depreciation, colour shift, energy efficiency

1 Luminaire types and selection

The luminaires in this study are typical square luminaires (60 x 60 cm) intended for applications such as office spaces. The luminaires are designed to be placed in a modular recessed ceiling.

Luminaires have been selected based on an extensive survey realised in 2014 (first generation LED luminaires). The aim was to identify the available range of products and to select a variety of higher and lower performing products, based on performance criteria as declared by the manufacturer. In order to exclude unacceptable solutions for the occupants, some luminaires have been previously tested on visual comfort during a retrofit operation. In total for this study 18 luminaires of 9 different types are tested. For some luminaire types, we have several specimens, which enabled us to explore the variability of performances within a product delivery.

Table 1 gives a list of all selected luminaires and the main performance indicators declared by the manufacturer. The list is classified in decreasing order of performance for the lumen maintenance parameter. Knowing that the lifetime is always expressed as a median value (B50), the luminaire with the best rated lumen depreciation is listed first. Only for the Type 5 luminaire the lifetime was expressed with a different failing rate of 10% (B10). The lumen maintenance of L80/B10 at 50.000h was converted to the rated median (B50) useful life of 50.000h with a lumen maintenance of L85, given the manufactures information on dispersion of their luminaire performances. None of the manufacturers data provided information on the colour shift and only a few declare a colour consistency expressed in terms of Standard Deviation Colour Matching (SDCM).

Table 1 – List of luminaire types and declared performances

	Number specimens	Power (W)	Luminous flux (lm)	Colour consistency	Lifetime (LxBy)	Class
Type 3	2	39	3550	NA	L97/B50@50.000h	High
Type 9	1	39	3928	3 SDCM	L90/B50@50.000h	High
Type 5	3	39	2800	NA	L85/B50@50.000h	High
Type 1	3	36	3772	3 SDCM	L80/B50@50.000h	Medium
Type 4	2	37	4000	NA	L75/B50@50.000h	Medium
Type 2	3	31	3400	NA	L70/B50@50.000h	Low
Type 7	1	39	3600	NA	L70/B50@50.000h	Low
Type 6	2	37	3400	NA	L70/B50@30.000h	Low
Type 8	1	40	3400	NA	NA	Low

Luminaires with different optical systems were selected. Figure 1 illustrates the variability of solutions for the selected samples, which represent a snapshot of available products on the market in Europe in the year 2014. Most of the luminaire types make use of diffusing materials in order to hide the bright LED chips. Others rely on a recessed position of the primary light source and reflecting surfaces. Some products also use a combination of these optical elements.

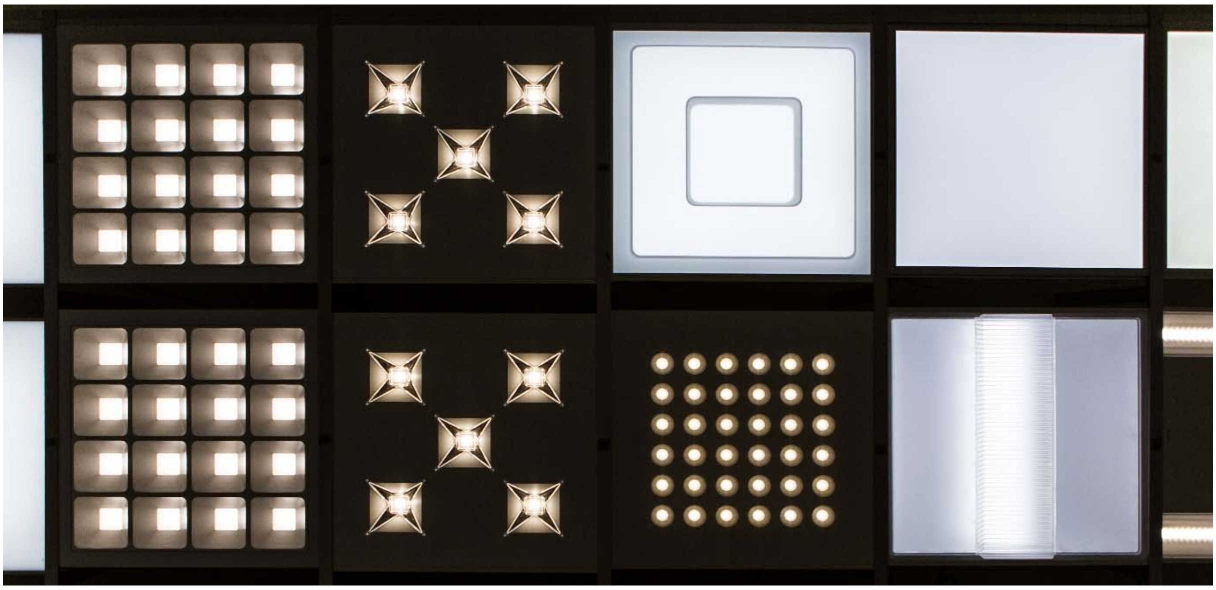

Figure 1 – Luminaire selection and optical systems

2 Test method

The luminaires were mounted on a metallic structure suspended at the ceiling of a test room. A special box-shaped structure was used to isolate the contribution of each luminaire during the photometric measurements. The tight connection with the ceiling support structure ensures that no parasite light from within the room enters the volume inside the box where the measurement instrument is placed. The interior surface of the box is coated with a black absorbing surface.

2.1 Test conditions

The experimental conditions that were chosen are not intended to match a normalised endurance test. Standards often prescribe operating conditions in terms of temperature and sometimes switching cycles. The principle of the accelerated temperature test is to substitute normal operating temperatures in order to quickly forecast the endurance of the product. For practical reasons testing duration is often limited to less than 6000 h (IEC, 2014; IES, 2008; IES 2015). The reference standard for LED modules (IEC 2014) specifies to measure the lumen output values at 1 000 h intervals. The collected measured data can then be used for lifetime projections. Standard models (IES 2011) and experimental models (Wagner *et al.*, 2017, Shailesh *et al.*, 2018) exist, but predictions vary with the method used for extrapolating the accelerated test data. It is often stipulated that any projection may not exceed a pre-set multiple of the actual tested hours. However, laboratory test conditions do not necessarily reflect real-world operating conditions, so there may be differences between predictions and practical experiences with lamps and luminaires in the field.

LED luminaires contain various subsystems including optical, electrical and thermal systems, and the reliability of the luminaire relies on the weakest point in the subsystems. The industry has done a lot of research on component level failure, but not much information is available for system-level reliability. The purpose of our test is to assess experimentally the endurance of performances at luminaire level. According to the standards, LED luminaires are expected to be tested for lumen maintenance at the ambient temperature in a temperature interval fixed around the rated ambient performance temperature, declared by the manufacturer. For our tests, the luminaires are kept switched on continuously, which is probably not a worst case for the electrical components but could be an interesting case for assessing parametric failure. Luminaires were installed in a hygrothermal-monitored test room. Temperature and relative humidity were registered every half an hour. The temperature in the room fluctuates between 20°C and 28°C. The average temperature is slightly higher than 24 °C and no temperature above 28°C was recorded. Relative humidity varies more, but registered values are always between 15% and 65%.

2.1.1 Time intervals and total duration

We measured several photometric and electric parameters for each luminaire at regular time intervals. The initial measurements were done a few hours (minimum 4 hours) after switching on the luminaire so that the reference value refers to the light output of the LED luminaire when it is fully warmed up. Initial performance of the luminaire was set as the reference value of 100%. The further measurements were set out in relative terms to that initial performance. After the initial performance tests, the subsequent measurements were done at time intervals between 2000 and 5000 hours. All luminaires have been measured up to operating times of 26.000 hours and some of the first installed types up to 31.000 hours.

2.1.2 Photometric and electrical performance parameters

For each luminaire the photometric parameters were measured inside the black box at 4 control points placed close to the vertical axis in the centre of the luminaire. The control points were placed in the symmetry axis of the luminaire to detect changes in the light distribution diagram. This way, abrupt failures of some individual led chips should possibly be detected. At each given time interval, we measured following characteristics:

- Illuminance at test points (lx).
- u' and v' chromaticity coordinates
- Spectrum (ranging from 380 to 780 nm with a bandwidth of 10 nm)

The electrical characteristics of a luminaire were measured with a professional power analyser. All luminaires are connected to the same power line, equipped with a timer and an energy meter. A specific switching board was constructed, allowing to connect the feeding line of each luminaire with the measurement instrument without the need to shut down. A specific switch dedicated to each luminaire is used during this procedure.

Electrical measurements are done at a lower frequency than the photometric measurements. At each time step for the measurement the following parameters were registered:

- Current (A) and tension (V)
- Input power (W)
- Power factor

2.2 Measurement equipment

The measurement equipment that is used to collect illuminance and spectral data, has a very good spectral match. This is particularly important for reliable readings of a typical spectrum emitted by a LED source. The instrument for the test is a Konica Minolta CL-500A with a f_1' index of less than 1,5 according to DIN 5032 part 7. Following the same standard, the general classification of the instrument is class B. The accuracy of the instrument given for colorimetric coordinates xy is +/- 0,0015 and the repeatability is 0,0005. Repeatability of measurements under our test conditions was confirmed for u'v' coordinates with a reproducibility test. Besides chromaticity coordinates u' and v' the spectral power distribution, colour temperature and peak wavelength was also registered.

For the measurement of the electrical parameters a Yokogawa WT 3000 Precision power analyser was used. This instrument has excellent stability and a basic power accuracy of 0,02%.

3 Results

3.1 Lumen maintenance

After 26.000 hours of continuous operation, the variation of performance between luminaires is significant. It should also be noted that none of the luminaires selected failed abruptly. Figure 2 gives the measured light output for each luminaire and at different moments. The coloured and non-outlined bars show the relative light output of the luminaire after several operating times compared to the initial value (0 H) set to 100%. For the comparison with performances announced by manufacturers (assuming a linear depreciation path) the black outlined bars without filling are represented.

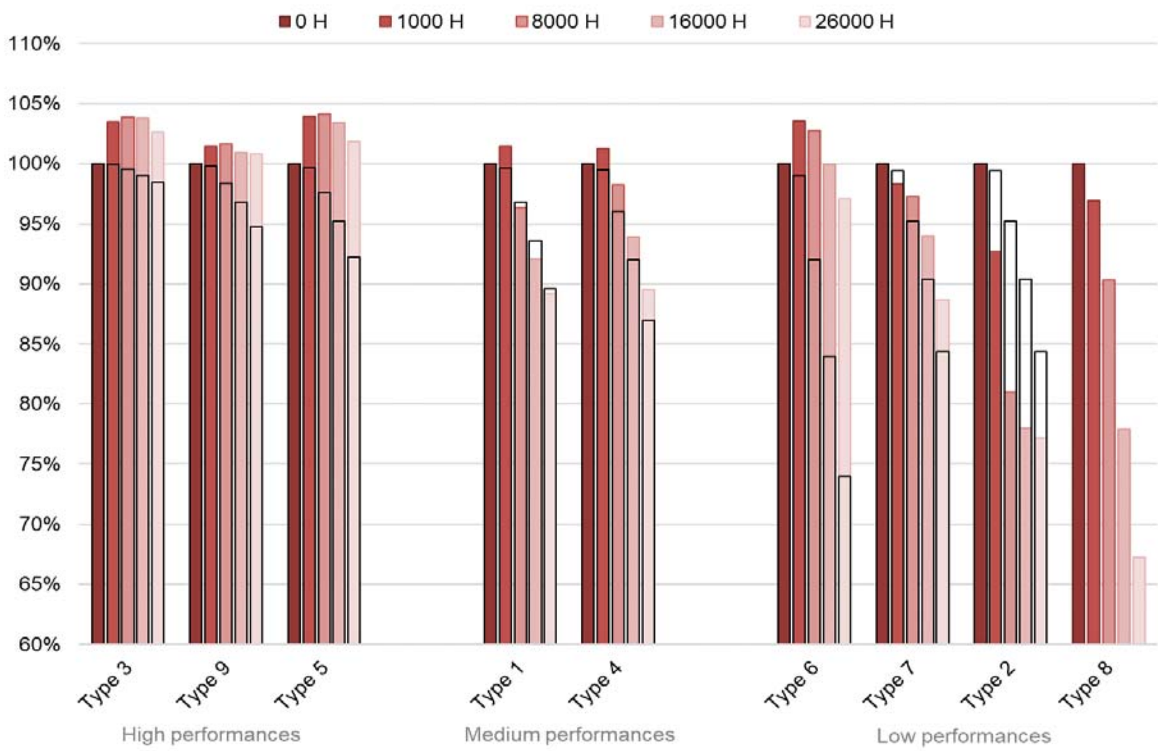

Figure 2 – Summary of results for lumen maintenance

All luminaires with a high-performance class for lifetime have a light output that is still above the initial value, which means that there is no real depreciation for these products. Luminaire types with medium announced lifetime performance seem to match well with the announced lumen depreciation. The lower performing products have the biggest divergences between declared and measured performance and between different specimens. The Type 8 luminaire, which didn’t give any data for lumen maintenance, drops to 67% of the initial measured value at 26.000h, while the Type 6 in this same luminaire performance class remains close to 100%. We could not identify if the luminaires have a lumen compensation functionality integrated in the drivers, however the measured voltage and current is very stable for all luminaires.

In general, the lumen maintenance of all luminaires is equivalent or better than what is announced by the manufacturer. Exceptions are observed for two product types (Type 1 and 2). While the Type 1 luminaire differs only very slightly from the expected course, Type 2 shows a notable variation already within the first few thousand hours after switching on the luminaire.

Figure 3 illustrates the lumen maintenance curve for the 4 products in the lower performance class in function of the operating hours. The Type 6 and 7 luminaires have a quasi-linear lumen maintenance curves up to 26.000 hours. The luminaires of Type 2 have an atypical depreciation course that quickly drops below 85% of initial light output after less than 3.000 hours and subsequently shows a more stable evolution. On the contrary, the luminaire of Type 8 has a regular depreciation curve in a first phase, and then the light output seems to decrease more strongly after approximately 12.000 hours.

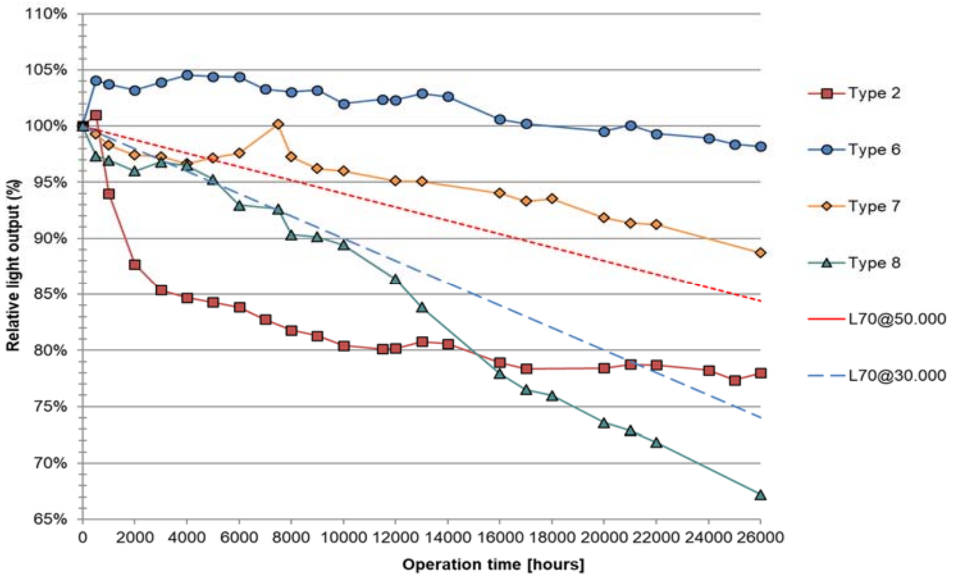

Figure 3 – Lumen depreciation curves for low performing class of products

Based on available product data it is impossible to anticipate the lumen depreciation such as shown for the luminaires Type 2 and Type 8. Even more, too often typical maintenance factors are used for a lighting design in practice. Unless the lighting installation was seriously oversized, the requested illuminance levels on the task area and the surrounding areas will become quickly insufficient when using this kind of luminaires in an office space for example. This would cause discomfort or could even create unsafe situations for the occupants.

3.2 Colour shift

The colour shift is the result of a deviation of the emitted spectrum of light compared to the characteristics of the initially produced spectrum due to ageing mechanism. Factors impacting chromaticity point stability in LEDs include ageing of the emitter, phosphors, encapsulant materials or even secondary optical elements (NGLIA, 2017). For example, products with PMMA diffusers would typically show a shift towards the yellow area of the colour space when thermal oxidation appears (Lu *et al* 2016). But a shift towards warmer light could also be caused by the effects of delamination and cracking when phosphor silicone components are used (Wagner *et al.,* 2017).

The measurements indicate that all luminaires have a typical spectral power distribution (SPD) corresponding to a blue led and phosphor technology, which results in a significant peak in blue wavelengths (peak wavelength between 446 and 455 nm). Initial values for chromaticity coordinates and values at several time intervals were measured. The magnitude of chromaticity shift can be quantified using Δu'v'. Table 2 gives the maximal chromaticity shift for each luminaire and the operating time when the colour shift reaches 3 SDCM. This threshold was chosen because at this level of colour shift most observers will perceive differences in normal conditions. The results indicate that 4 out of the 9 types of luminaires do not limit colour shift below 3-steps u'v' in test conditions, so they could be perceived as disturbing.

Table 2 – Maximal colour shift and operating time at 3 SDCM deviations

Luminaires	Δu'v' Specimen 1	Δu'v' Specimen 2	Δu'v' Specimen 3	Operating time at SDCM > 3
Type 3	0,0006	0,0007	-	/
Type 9	0,0003	-	-	/
Type 5	0,0016	0,0014	0,0015	/
Type 1	**0,0049**	**0,0046**	**0,0049**	16.000 h
Type 4	**0,0057**	**0,0056**	-	16.000 h
Type 2	**0,0097**	**0,0099**	**0,0098**	1.000 h
Type 7	0,0027	-	-	/
Type 6	0,0026	0,0028	-	/
Type 8	**0,0035**	-	-	12.000 h

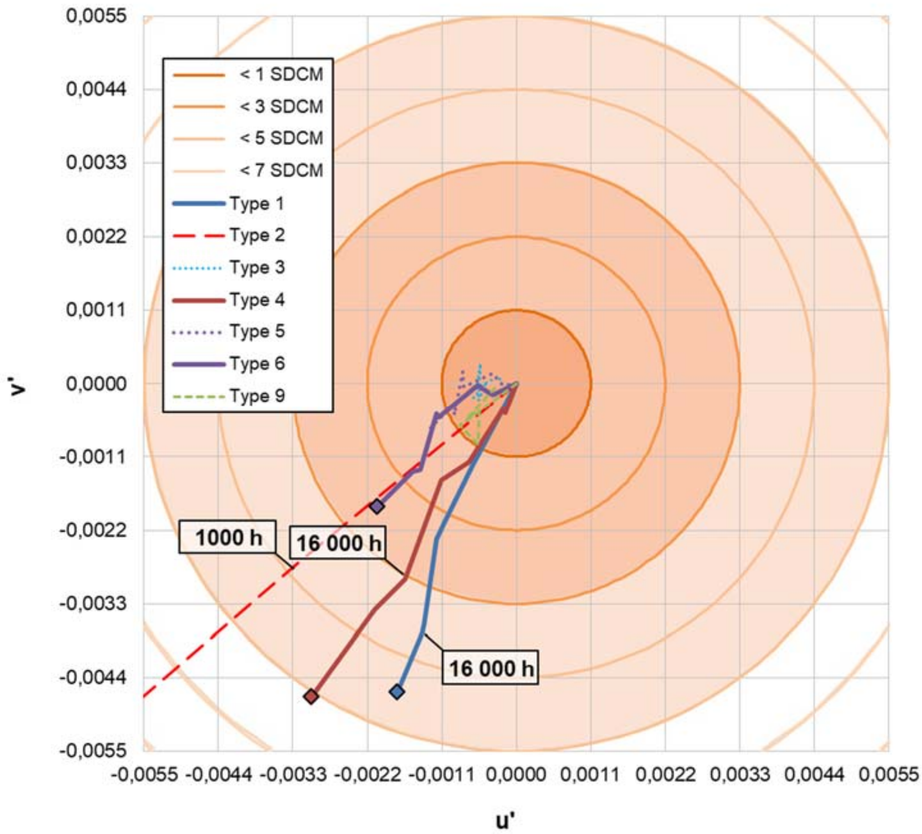

Figure 4 – Luminaires with a regular colour shift

In order to evaluate the directions of colour shift we use the CIE u',v' chromaticity diagram as it represents the most uniform colour space. Following the CIE technical note (CIE, 2014) concentric u'v' circles are used to approximate the MacAdam ellipses. An n-step u'v' circle is defined as a circle in the diagram with a radius of n times 0,0011. The centre point is set to the initial value measured for each luminaire. All luminaires tested reveal a very consistent colour shift pattern between specimens of the same type. Therefore, we only represent data for one specimen per luminaire type. It can be observed that the colour deviation is mostly shifting towards the blue region in the u’v’-diagram (colder colour temperatures) and that it progresses irregularly. High performance luminaires (Type 3 and Type 9) have a limited colour shift as values measured stay within 1-step u’v’ circle. The maximal deviation of chromaticity coordinates observed is close to a 9-step u’v’ circle for the Type 2 luminaire (outside the diagram of Figure 4). In this case the colour shift would be clearly perceived.

However, two luminaire types (Type 7 and Type 8) present a special colour shift pattern as shown in Figure 5. First, the deviation proceeds in one specific direction up to the measurement time of 12.000 hours for Type 7 and 16.000 hours for Type 8, and then the colour shift appears to be moving in a nearly opposite direction in the chromaticity diagram. In an initial stage for the Type 8 luminaire a yellow shift appears, and then a blue shift is initiated after the inflexion point. This suggests that various ageing mechanisms occur, and that one can overrule another over time.

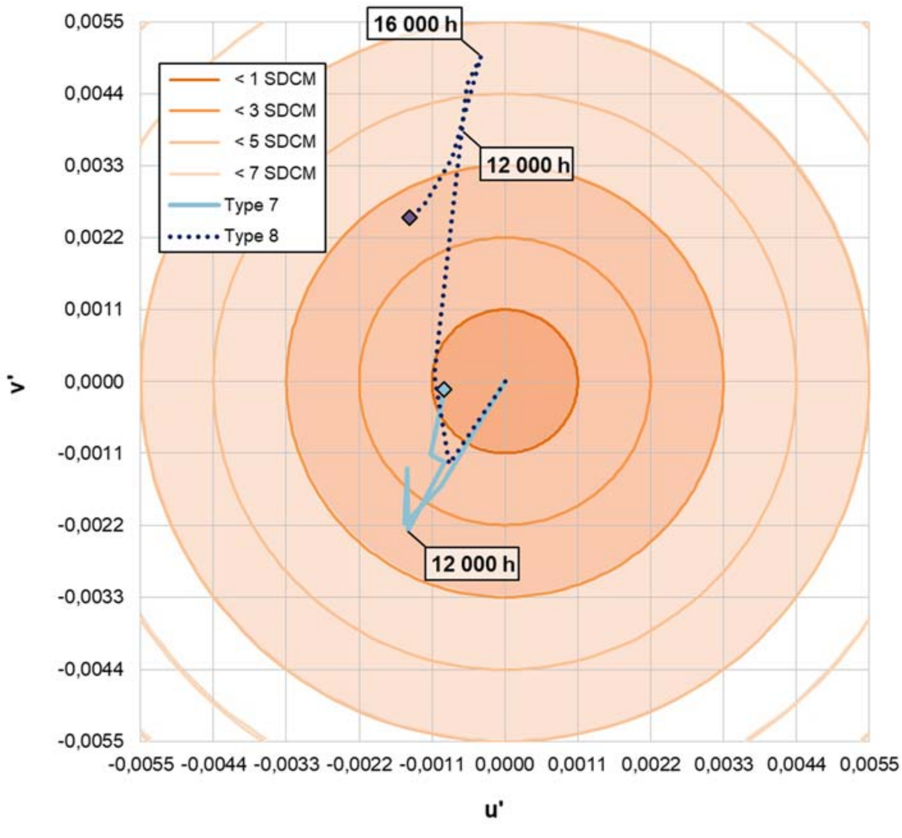

Figure 5 – Luminaire with an irregular colour shift pattern

As none of the manufactures gave information on colour shift, we could not compare these results with the predicted performance. A few manufacturers specify the colour consistency of their product, which means that they guarantee a maximal colour shift between different models of a same luminaire at initial stage. Chromaticity maintenance prediction methods are even more challenging than lumen depreciation projections. The newer standard (IES, 2015) require reporting on the individual chromaticity coordinates (u’ and v’) instead of the total shift (Δu'v') but cannot handle the inflexions of chromaticity deviations observed.

3.3 Photometric performances in restart mode

After all luminaires reached a minimum of 26.000 h operating, they were switched off for one week so they could reach an equilibrium with the room temperature again. Then a restart process was done where we measured the light output and the colour coordinates in short timesteps of 1 minute for the first 20 minutes, and then after approximately 6 and 20 hours. The purpose of this set of measurements is to check if a convergence to the value that was last recorded before shutting down the luminaires is realised and also if a warm-up time and drift can be observed. In principle, luminaires with a good thermal management should converge rather slowly to the equilibrium state, while luminaires which raise more rapidly in temperature would show a quicker convergence. In this sense the characteristics when starting up a luminaire could be a good indicator of reliability.

Most luminaires show an instant increase in lighting output and then a slow decrease and convergence to the last recorded measurement before shutting down. The first measurement after restarting vary up to 5,3% for the luminaire of Type 2. Only two luminaire types (Type 7 and Type 8) do not show a higher measured illuminance at restart. These are also the two luminaires which have the irregular colour shift patterns. At a time interval of 6 h the measured values were all within 1% of the last recorded reference value, but full convergence occur after approximately 24h.

Colour shift is a different issue. All luminaires converge nearly perfectly to the last recorded chromaticity coordinates before shutting down, but the drift measured at restart exceeds a 2-step u'v' circle. Even high performance luminaires, which present a maintained chromaticity below 1-step u'v' (see section 3.2) have a more significant colour shift when starting up (Figure 6). After 6 h operating time the Type 5 luminaire is still at Δu'v' of 0,0021. It also reaches its initial chromaticity coordinates only after more than 20h of operation.

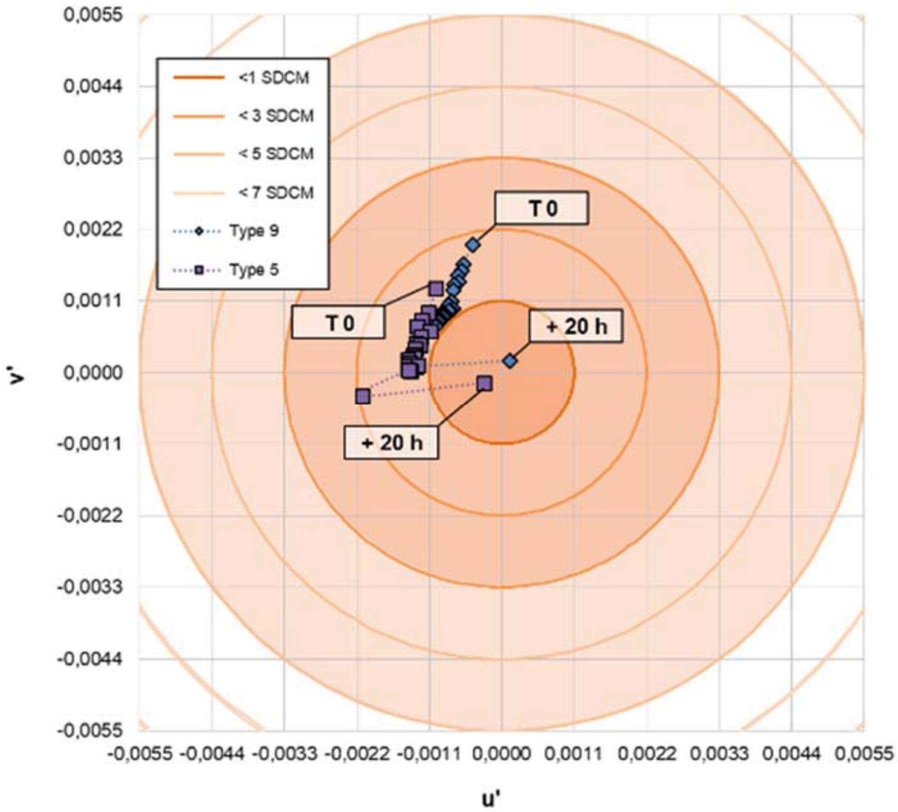

Figure 6 – Variations of chromaticity coordinates for high performance luminaires after restart

3.4 Input power

The electrical power taken by the luminaire is given in Table 3. The first line gives the rated power as noted on the technical documentation of the manufacturers. In the second and third line the power consumption of the luminaire is written at initial stage and after the total test duration. Except for the luminaire Type 2 all measured power is within 1% of the initial values. However, the differences with the rated power is more important. Mostly the luminaires consume less power than declared, except for the Type 3, Type 7 and Type 9 luminaires. But we observe that only for the Type 7 luminaire the electrical power consumption is significantly higher than rated (14,2%).

Table 3 – Measured initial and maintained power consumption

Luminaire	Type **1**	Type **2**	Type **3**	Type **4**	Type **5**	Type **6**	Type **7**	Type **8**	Type **9**
Rated Power	*36*	*31*	*39*	*37*	*39*	*37*	*39*	*40*	*39*
Initial	34,6	30,5	39,7	36,2	37,0	34,9	44,6	37,9	39,3
Final	34,6	30,1	39,3	36,1	36,6	35,1	45,0	38,0	39,2

Because the energy taken by the luminaire is nearly constant over time, the energy efficiency depreciates in a similar way to the lumen depreciation. Based on the registered lumen depreciation the calculated energy efficiency of the luminaire of Type 2 would drop from 111 lm/W to 86 lm/W.

4 Conclusions

Regarding the lumen maintenance, most products tested fulfil their promises in the conditions of this test, but an important variability has been noticed. Just 2 out of 9 types of luminaires do not meet the expected lumen decrease limits, but 2 types also clearly outperform positively. The products where the light flux reduced faster than declared both have a relatively low lumen maintenance factor of 70% at different lifetime intervals following the manufacturers data. Furthermore, they show a bigger dispersion of results between different samples of the same type of luminaires.

The colour shift appears to be more problematic. For 5 out of 9 luminaire types tested, the colour shift is limited to levels that are not noticeable by most observers. For the other luminaire types a chromaticity deviation exceeding 3 SDCM, at any moment during the test, was measured. The variation of the emitted spectrum of light can be caused by several cumulating ageing processes. The result is that irregular colour shift patterns with inflexion points can occur. We also noticed that the loss in energy efficiency of luminaires is equivalent to the relative light flux reduction because the input power stays nearly constant.

It is difficult to detect a consistent depreciation pattern for the endurance parameters at system scale. Even if the observed results vary between the luminaires types tested, it seems there is a correlation between lumen maintenance and colour shift, as best products perform better in both criteria. We suggest that frequent measurements when starting up could be an indicator for luminaire reliability.

It is generally thought that the degradation of lumen output of the LED sources in the luminaire is the determinant factor for lifetime assessment. However, this is only one factor for the complete product reliability. Further research is needed to identify better methods and models that integrate the failure mechanisms in the various luminaire subsystems in order to deliver more accurate lifetime claim from LED luminaire.

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