Replacing light sources and the need to determine the technical luminous coefficients

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Abstract. In this work, the authors present the necessity of photometric measurements in order to determine quality parameters when changing light sources with other types of light sources. To emphasize this we conducted a case study, measuring luminous parameters on two different streets, and we determined the technical luminous coefficients that establish the lighting system quality. We made photometric measurements on a street with sodium vapours lamps and on a street with LED lamps, determined the technical light parameters and did a comparison of the results. The outcome of the case study underline the need of conducting photometric measurements and of the lighting system redesign such that, upon changing the light sources and the technical characteristics of the lighting systems, the system still fulfils the technical standards requirements. In conclusion, for each space that is to be illuminated, an optimal solution should be found, which ensures both a reduction of the energy consumptions (reducing the system’s costs) and meets the technical lighting requirements.

1. Introduction

Increasing energy efficiency by reducing consumption and acquiring wares with high energetic efficiency has been imposed by two European directives to all EU states in 2012 [1], [2]. In Romania, the law states that until 2020 the electric consumption must be reduced by 19% [3]. At a global level, the light sources energy consumption makes 19% of the total [4]. This percent is considered to be large, so the requirement to change the inefficient light sources with better ones was introduced. More and more countries have switched to using LED light sources. According to [5]:
- Switzerland and Thailand forbade the sale of low efficiency light bulbs in 2007;
- In 2008 Australia banned the import and sale of white heat light sources;
- Ireland banned the sale of low efficiency light sources in 2009;
- Great Britain forbade the use of white heat light sources in 2011;
- Since 2014, U.S. of A. finished replacing white heat light bulbs used in public areas with more efficient one, a process started in 2012;
- Since 2012, India runs a project to replace white heat light bulbs.

Since 2010, more and more cities replace their low efficient light sources with higher efficacy sources, which lead to significantly lower electric power consumption. For example, the Mociu town reduced its power consumption by 72% [6], and the city of Bași – reduced its electric bill by 80% [7].
Other cities around the world have changed their old light systems to use LED sources: Copenhagen reduced its electric power consumption by 57% in 2016 by changing half of its street lights to use more efficient light sources [8]. In Rome, investing in LED light sources could be written-off in 5 years [9]. In most of the cases, for outdoor lighting systems, the change in light source is done without doing any photometric measurements, by which lighting coefficients would lead to the choice of an optimal light source. Again, in many cases, the light sources installations’ layouts do not correspond to the design project data (light source placement, height, light crutches length, inclination angle, etc.). Furthermore, lighting system designs are not optimized to take into consideration the peculiarities of the spaces to be illuminated, and do not respect European standards for road lighting [10], [11]. The trend towards intelligent cities must take into consideration reduced light pollution, higher energy efficiency, and conforming to luminous coefficients defined in these standards. In addition, the road lighting systems must allow for pedestrian face recognition, which, in turn, adds new constraints to the (pedestrian) road lighting [12]. The efficiency of road lighting systems can be increased by monitoring systems with sensor networks that communicate wireless [13]. In February 2018, Romania has launched “Operation C – Public Lighting” of the Priority Axis 3-3.1, “Supporting energy efficiency and renewable energy use in public infrastructure, including public buildings and housing,” financed through the Regional Operational Programme, POR 2014-2020 [14]. The Programme guidelines require that photometric measurements are done before and after the light sources are replaced.

In this paper we analyse the lighting system on a four lane, two traffic direction street, measuring light parameters before and after replacing the sodium-vapour light sources with LED sources. We compare the latter with the values required in street lighting technical standards and norms, and propose a better design for the light system such that the technical parameters are improved.

2. A lighting system with sodium-vapour lamps
We analyse a lighting system with sodium-vapour lamps located on a four-lane road (see Figure 1).

![Figure 1. A four-lane road with a sodium-vapour lighting system.](image)

The dimensions of the road and lighting system areas are:
- Road surface width for one traffic direction (two lanes) is 7.08 m;
- The middle green space width is 22.35 m;
- Distance between light posts is 35.5 m;
- Light post height is 35.3 m;
- Console length is 6 m;
- The number of luminaires per light pole is 2;
- The distance from the light pole to the road surface is 6 m.
We took measurements at 55 uniformly distributed points on the road surface between two consecutive light poles. The measurements were done on a night with clear sky, and dry road surface. The road surface is illuminated by sodium-vapour light sources, with a 17,500 lm luminous flux, a 2,100 K colour temperature, 150 W source power, and 171 W total absorbed power. Figure 2 shows the photometric curve for these light sources.

Figure 2. Photometric curve for a sodium-vapour light sources.

For each of the 55 points we measured the illumination and luminance levels. Table 1 presents the values we registered.

| The measured illuminances levels |
|----------------------------------|
| 31.5 26.5 16.2 11.6 11.2 12.2 14.0 17.5 21.4 44.3 49.0 |
| 28.1 23.7 14.9 11.3 10.4 11.9 13.0 16.9 21.5 43.6 47.0 |
| 22.3 16.7 13.9 10.3 9.6 11.2 11.9 15.7 18.6 36.3 40.3 |
| 18.6 12.3 14.3 9.8 9.4 10.8 10.7 13.5 15.6 29.6 32.5 |
| 15.4 11.6 9.8 9.2 8.7 10.0 10.7 12.3 13.2 22.6 24.5 |

These fall between 8.7 lx and 49 lx, with an average illumination of 18.66 lx. Using equations defined in guide and manual books [15], [16] and given in standardization documents [17], [18], we compute the general illuminance uniformity:

\[ U_0(E) = \frac{E_{\text{min}}}{E_{\text{med}}} = \frac{8.7}{18.7} = 0.465 \]  

and the illuminance uniformity:

\[ U_0'(E) = \frac{E_{\text{min}}}{E_{\text{max}}} = \frac{8.7}{49} = 0.177 \]
Table 2 shows the luminance values measured in the 55 points on the road surface. The values fall between 0.15 cd/m² and 2.47 cd/m², with an average luminance of 0.57 cd/m². The minimal luminance values measured on the axes of the two road lanes are $L_{\text{min}1} = 0.30$ cd/m², $L_{\text{min}2} = 0.17$ cd/m², while the maximum luminance values are $L_{\text{max}1} = 1.56$ cd/m², $L_{\text{max}2} = 0.80$ cd/m².

| The measured luminance levels |
|-------------------------------|
| 1.41 1.33 0.86 0.64 0.53 0.51 0.58 0.89 1.08 2.25 2.47 |
| 0.86 0.73 0.43 0.39 0.30 0.30 0.38 0.47 0.86 1.32 1.56 |
| 0.46 0.43 0.21 0.17 0.15 0.20 0.23 0.33 0.30 0.55 0.65 |
| 0.44 0.42 0.25 0.21 0.17 0.19 0.19 0.25 0.32 0.49 0.80 |
| 0.31 0.54 0.37 0.29 0.24 0.17 0.22 0.36 0.30 0.45 0.40 |

Using equations defined in guide and manual books [15], [16] and given in standardization documents [17], [18], we compute the general luminance uniformity to be:

$$U_0(L) = \frac{L_{\text{min}}}{L_{\text{med}}} = \frac{0.15}{0.57} = 0.263$$

and the longitudinal luminance uniformities to be:

$$U_{11}(L) = \frac{L_{\text{min}1}}{L_{\text{max}1}} = \frac{0.3}{1.56} = 0.192$$

$$U_{12}(L) = \frac{L_{\text{min}2}}{L_{\text{max}2}} = \frac{0.17}{0.80} = 0.213$$

3. A lighting system with LED lamps

For this study, we replaced the sodium-vapour light sources with LED light sources, with a maximum power of 127 W, a nominal luminous flux of 16,360 lm, outgoing luminous flux of 13,740 lm, and the colour temperature of 4,000 K. Figure 3 shows the photometric curve of these LED light sources.

For the same street and light system placement as shown in Figure 1 we did a new set of luminance and illumination measurements. Table 3 shows the illuminance values, which fall between 8.1 lx and 27.2 lx, with an average of 17.463 lx. The general illumination uniformity is:

$$U_0(E) = \frac{E_{\text{min}}}{E_{\text{med}}} = \frac{8.1}{17.463} = 0.464$$

and the illuminance uniformity is:

$$U_0'(E) = \frac{E_{\text{min}}}{E_{\text{max}}} = \frac{8.1}{27.2} = 0.298$$

| The measured illuminances levels |
|-------------------------------|
| 16.9 24.9 23.3 19.1 18.6 21.2 17.9 19.2 22.0 23.6 18.7 |
| 16.5 27.2 22.4 17.1 15.6 17.5 15.3 18.6 22.0 26.8 22.3 |
| 18.8 21.5 18.5 13.9 12.0 12.3 12.7 15.3 19.1 26.5 25.8 |
| 20.3 18.9 14.8 12.3 10.2 9.1 11.9 12.7 15.1 21.2 23.6 |
| 18.6 16.4 13.1 10.9 9.2 8.1 10.2 11.7 12.6 17.5 19.0 |
Table 4 presents the luminance values measured in the 55 measurement points on the road pavement. The values fall between 0.17 cd/m$^2$ and 1.05 cd/m$^2$, with an average luminance of 0.63 cd/m$^2$. The minimal luminance measured on the two lane axis are $L_{min1} = 0.5$ cd/m$^2$, $L_{min2} = 0.31$ cd/m$^2$, while the maximum luminance values on the same area are $L_{max1} = 0.97$ cd./m$^2$, $L_{max2} = 0.74$ cd./m$^2$.

Using equations defined in guide and manual books [15], [16] and given in standardization documents [17], [18], we compute the general luminance uniformity to be:

$$U_0(L) = \frac{L_{min}}{L_{med}} = \frac{0.17}{0.63} = 0.269$$

and the longitudinal luminance uniformity to be:

$$U_{11}(L) = \frac{L_{min1}}{L_{max1}} = \frac{0.5}{0.97} = 0.515$$

$$U_{12}(L) = \frac{L_{min2}}{L_{max2}} = \frac{0.31}{0.74} = 0.419$$

Figure 3. Photometric curves for LED light sources.
4. Comparative analysis of the two lighting systems

Table 5 presents the technical and luminous parameters computed for the two lighting systems. To determine their compliance with the normative requirements, we compare these parameters with the standardised values specific to the road analysed.

| Parameter                              | Sodium-vapours sources | LED source | Values required by standards |
|----------------------------------------|-------------------------|------------|-----------------------------|
| Power [W]                              | 171                     | 127        | -                           |
| Source flux [lm]                       | 17500                   | 16360      | -                           |
| Colour temperature [K]                 | 2100                    | 4000       | -                           |
| $E_{\text{min}}$                       | 8.7                     | 8.1        | -                           |
| $E_{\text{med}}$                       | 18.66                   | 17.46      | $\geq 10$                   |
| $E_{\text{max}}$                       | 49                      | 27.2       | -                           |
| $U_0(E)$                               | 0.465                   | 0.464      | $\geq 0.4$                  |
| $U'(E)$                                | 0.177                   | 0.298      | -                           |
| $L_{\text{min}}$                       | 0.15                    | 0.17       | -                           |
| $L_{\text{med}}$                       | 0.57                    | 0.63       | $\geq 0.75$                 |
| $L_{\text{max}}$                       | 2.47                    | 1.05       | -                           |
| $U_0(L)$                               | 0.263                   | 0.269      | $\geq 0.4$                  |
| $U_{11}(L)$                            | 0.192                   | 0.515      | $\geq 0.6$                  |
| $U_{12}(L)$                            | 0.213                   | 0.419      | $\geq 0.6$                  |

4.1. Photometric curves

Comparing the photometric curves of the two lighting systems we immediately see that the sodium-vapours source is inefficient for long distances between light posts. This is because the luminous intensity after the ± 45° direction, in the (0°-180°) plane is 148.75 cd, while on the ± 60° direction the intensity is of 140 cd. The illumination along these lines strongly influences the illumination and luminance uniformity between poles. For LED light sources, on the same direction lines, the luminous intensity is of 3599.2 cd and 9979.6 cd, respectively. This is 24 and 71 times bigger than intensity given by the sodium-vapour sources. Therefore, the LED light sources can ensure a better illumination uniformity.

4.2. Absorbed electric power and the emitted luminous flux

The electric power absorbed by the LEDs represent 74.27% of the electric power absorbed by the sodium-vapour light sources. This shows an energy saving of 25.73% compared to the current situation, for the studied road area.

The LED luminous flux makes 93.48% of the sodium-vapour light sources flux, which is a decrease of only 6.52% for an absorbed power decrease of 25.73%.

4.3. Luminous efficiency

For the two luminous sources we analysed, the luminous efficiency is:

$$e_{\text{sodium}} = \frac{\Phi}{P} = \frac{17500}{171} = 102.34 \text{ lm/W}$$

$$e_{\text{LED}} = \frac{\Phi}{P} = \frac{16360}{127} = 128.82 \text{ lm/W}$$

It is obvious that the LED light sources are with 26% more efficient than the sodium-vapour ones.
4.4. Colour temperature
Figure 4 shows the Kruithof diagram which displays the dependency between illumination and colour temperature [19]. It is noted that for a 2,100 K colour temperature, the visual comfort zone is very limited (10 lx÷ 20 lx), which limits the use of sodium-vapour light sources. At 4,000 K colour temperatures, the visual comfort zone is wide (200 lx÷ 9000 lx), which makes LED light sources a good choice for illuminating large spaces. In addition, LED lamps favour correct colour and face recognition.

4.5. Illumination and illumination uniformity
Looking at the average illumination and the general illumination uniformity, both types of light sources show values superior to the ones required by standards and norms. The large difference between the minimal and maximal illumination values determined for the sodium-vapours light sources (8.7 lx vs. 49 lx) causes visual discomfort, as eyes have to adapt to the different values. LED light sources have a smaller gap between the minimal and maximal values (8.1 lx vs. 27.2 lx) on the surface we analysed.

4.6. Luminance and luminance uniformity
Both types of light sources (LED and sodium-vapour based) show lower values for the average, general and longitudinal uniformity luminance than the ones specified in standard and norms. The luminance we measured for the sodium-vapours light sources show a big gap between minimal and maximum values (0.15 cd/m^2 vs. 2.47 cd/m^2) which leads to a general luminance uniformity a half than the minimum required by the specific norms.

4.7. Light source emplacement system
According to our field observations, the light system did not have the correct emplacement configuration to comply with technical luminous parameters required for such a street.

5. Redesigning the light system
We describe, here, our redesign of the light system such that it complies with the standards and norms. The simplest and most direct solution is to place the light posts at a 1 m distance from the road side, on the central green area, where the distance between the posts stays the same as in the original design. Figure 5 presents the new emplacement configuration, for one traffic direction. The configuration is the same on the other direction.
Figure 5. New light post emplacements for one traffic direction.

Figure 6 presents the illumination and luminance contour lines for the two traffic directions for the new design. Figure 7 presents the luminance contour lines for the two traffic directions for the new design. Table 6 compares the technical light parameters for the improved design using LED light sources.

Figure 6. Illumination contour lines.

Figure 7. Luminance contour lines.
Table 6. Technical and luminous parameters.

| Parameter | LED source with the old system | LED source with the proposed solution | Values required by standards |
|-----------|-------------------------------|----------------------------------------|-----------------------------|
| $E_{\text{min}}$ | 8.1 | 7.31 | - |
| $E_{\text{med}}$ | 17.46 | 11 | $\geq 10$ |
| $E_{\text{max}}$ | 27.2 | 21 | - |
| $U_0'(E)$ | 0.464 | 0.636 | $\geq 0.4$ |
| $U_0'(E)$ | 0.298 | 0.354 | - |
| $L_{\text{med1}}$ | 0.63 | 0.85 | $\geq 0.75$ |
| $L_{\text{med2}}$ | 0.63 | 0.93 | $\geq 0.75$ |
| $U_0(L_1)$ | 0.269 | 0.45 | $\geq 0.4$ |
| $U_0(L_2)$ | 0.269 | 0.46 | $\geq 0.4$ |
| $U_{11}(L)$ | 0.515 | 0.60 | $\geq 0.6$ |
| $U_{12}(L)$ | 0.419 | 0.60 | $\geq 0.6$ |

6. Conclusions
To upgrade lighting systems to a more efficient utility and energy consumption, it is not enough to only replace the light sources. It is necessary that the other lighting system parameters are changed. In our example, repositioning the light posts optimized the luminous parameters on the road we studied. The light source photometric curves must weigh heavily when choosing the light sources for the light system. The aim is that the light intensity along the $\pm 45^\circ$ and $\pm 60^\circ$ angles is high. In addition, mounting the luminaires must be done such that the highest light intensities are along the lane axis of the road.

The next steps in our research are to analyse various types of LED sources to find the optimal lighting parameters for specific spaces.

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