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***Abstract*— Light emitting diodes (LEDs) are commonly expected to be the future of lighting because of a high luminous efficacy, a long lifetime and a high color rendering index (CRI). Nevertheless, the performance and the reliability of an LED are strongly dependent on the LED junction temperature. This paper presents a multi-objective methodology to find the optimal forward current subject to the annualized cost of the luminaire (initial capital cost, replacement cost, operation and maintenance cost…) and the annualized energy consumption. A simple LED model based on empirical data has been developed and takes into account optical, electrical, thermal and ageing behaviour. Three different white LEDs have been evaluated through several combinations of forward currents and heatsinks to satisfy a given mission profile. A set of optimal solutions has been determined by Pareto optimization.**

Keywords*— *Life estimation, Light emitting diodes (LED), Light sources, Pareto optimization, system analysis and design, thermal modeling.

I. INTRODUCTION

Nowadays, the world is illuminated by more than 33 billion artificial sources. In 2005, the consumption of grid-based electric lighting was around 2 650TWh, about 19% of the total electricity consumption [1]. To reduce the increasing demand of electricity [2], the use of LED lamps with high electricity to light conversion efficiency is a promising solution. Indeed, the average efficiency is around 35% for LEDs, far better than the incandescent light bulbs with 5% and the fluorescent lamps with 20% [3]. The question of environmental impacts, even if it is a real issue, is not discussed in this paper. For more information on this subject, please refer to the article published by the U.S. department of energy (DOE) on the life cycle assessment (LCA) of incandescent, compact fluorescent, and LED lamps [4]. In this report, LED lamps appear to be the best solution in terms of life cycle energy consumption and were expected to be nearly twice better in a couple of years.

However, a complete manufactured LED lamp is still expensive and special care must be taken with light output and ageing that can be significantly affected by the operating temperature [5, 6]. Recent studies have reported the relationships between photometric, electrical and thermal aspects for LED systems [7-10].

To avoid thermal runaway, this type of lighting is powered by a power converter, also called LED driver, commonly running in continuous conduction mode (CCM) and regulated by a single current control loop, as in the example described in [11]. Other more complex control schemes have also been designed to use accurately and efficiently LED lamps [12, 13]. The control is crucial to ensure LED good performances since current waveform has photometrical and colorimetrical impacts on light emission [14]. Moreover, it also enables to avoid potential health issues inherited from LED flickering [15-17].

In this study, two criteria in conflict with each other must be satisfied simultaneously to find the optimal LED current: the cost of the luminaire and the energy consumption, both over 20 years. To solve this problem, a Pareto multi-objective optimization is proposed. Many systems are faced to the same problem, even with far more objectives to satisfy, especially in renewable power systems [18]. A recent paper presents the state of art of meta-heuristics methods used to solve multi-objective problems [19].

This paper is organized as follows: section II introduces the LED string specifications and the optimization method. In section III, the LED string combination and the study of LED luminous efficacy is presented and assessed for three different white LEDs. Section IV details the thermal model of an LED, while the ageing model of an LED is described in section V. The cost of an LED luminaire with heatsinks and the results of the proposed method are discussed in section VI.

II. OPTIMIZATION METHODOLOGY

In order to obtain a good quality of illumination, it has been chosen to control the current supplied in each LED of the luminaire. As LEDs have not exactly the same V-I characteristics, a simple configuration is to associate LEDs in a single string but it creates a reliability concern: if a LED fails as open circuit, the entire luminaire will be failed. A study [20] presents the different possible associations (single string, series string or series-parallel string) and a method to achieve current equalization.

The goal of our study is to evaluate a 3600 lm luminaire which corresponds to a common standard lighting device constituted by 3 fluorescent – 1200 lm tubes of 14W.

To evaluate the behaviour of the LED luminaire, different forward currents will be computed and a mission profile close to a typical shopping center lighting profile has been chosen, as described in Fig 1.

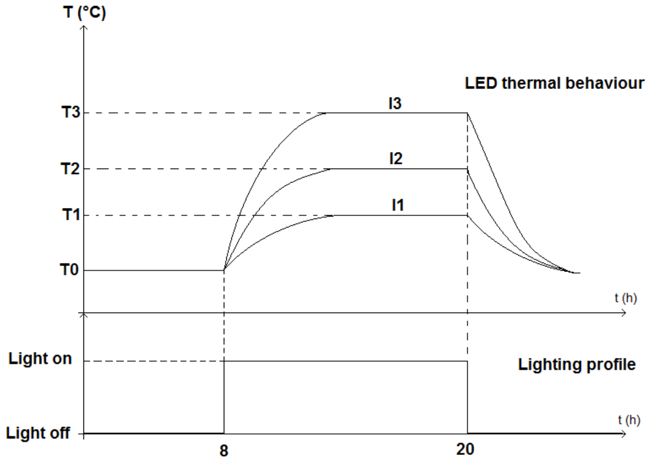

Fig. 1. Typical shopping center lighting profile

A Pareto optimization will be used to find forward currents making the best trade-offs between the annualized cost of the luminaire and the annualized energy consumption over 20 years. This method is used in many disciplines to find optimal solutions when objectives are conflicting. It is not convenient to deal with the price of energy because it varies from a state to an other, depending on the season, governmental rules... In our case, the main advantage of the Pareto method is to avoid the use of the price of energy, an arbitrary weighting coefficient, to compare the cost of the luminaire and the energy consumption. In multi-objective optimization, optimal solution is not unique, a set of non-dominated solutions is given and it forms the so-called Pareto front. Then, an expert will choose one solution among non-dominated solutions, regarding to his experience and convenience.

In an iterative and incremental way, all forward currents and LED combinations are simulated by using the LED model which will be developed in the next sections. In our case, currents from 50mA to 700mA will be evaluated. Currents below 50mA will not be computed because it implies a luminaire with a very large number of LEDs. Because the junction temperature of the LED will be too high and could damage the LEDs, currents above 700mA will not be computed too. A flowchart of the proposed method is illustrated in Fig. 2.

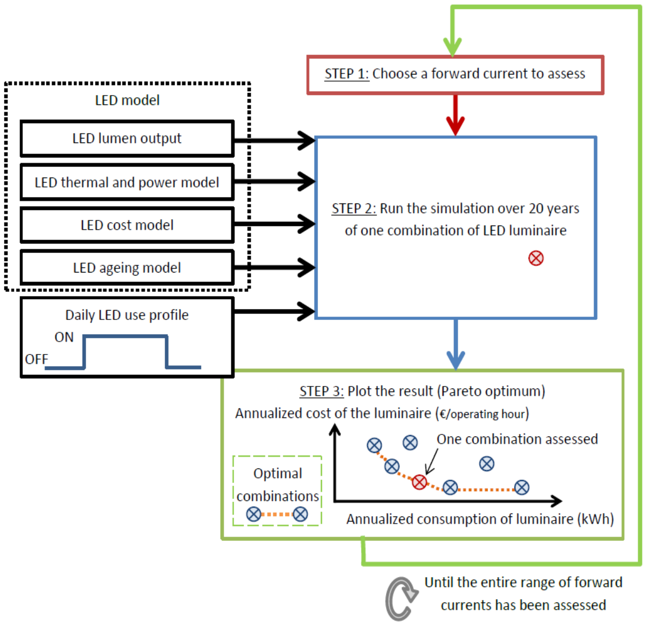

Fig. 2. Flowchart of the LED optimization methodology

Three different types of white LEDs with similar properties have been used for experiments. Main characteristics are gathered in Table I [21-23].

TABLE I
DATA FROM MANUFACTURERS OF LEDS USED FOR EXPERIMENTS

	Cree XTEAWT GE5	**Lumileds** LUXEON Rebel plus LX18-P140-3	**OSRAM** OSLON square 5L7N-1
Viewing angle (°)	115	120	120
Luminous flux (lm) at 85°C junction temp.	130 @350mA	103 @350mA	194 @700mA
Forward voltage (V)	3.4	2.85	2.85
Max. junction temp. (°C)	150	150	150
Max. thermal resistance junction/solder point (°C/W)	5	9	3.9
Price (€)	1.36	1.36	2.38

Experimental tests have been done with LEDs soldered on an aluminum printed circuit board (PCB). For each type of LEDs, three LEDs have been associated in series and the results have been averaged. A heatsink with a thermal resistance of 1.2 K/W has been added and silicone thermal grease with a conductivity of 0.9W/mK makes a good thermal conduction between the PCB and the heatsink.

In order to evaluate the thermal behaviour of an LED, a battery cycler BioLogic BCS-815 and temperature chamber ESPEC SU-221 have been used, Fig. 3.

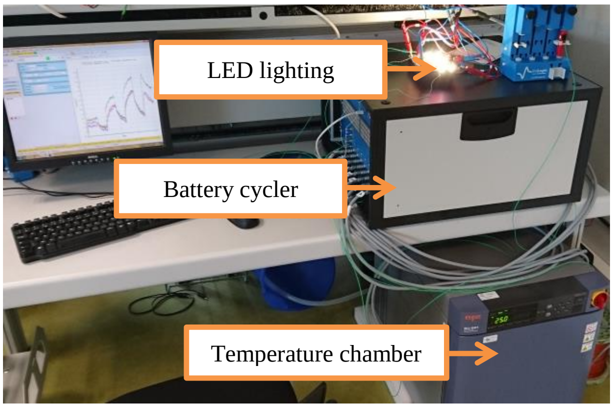

Fig. 3. Experimental setup assessing LEDs

III. LED LUMINOUS FLUX

To determine the number of LEDs that are needed to obtain the desired luminous flux, the luminous efficacy has been assessed with a sourcemeter Keithley 2602A, an integrating sphere and a spectrometer Specbos 1201 in a controlled temperature room (22°C). All measures have been done after 40 minutes to ensure that LEDs are thermally stabilized. The LED junction temperature is estimated, based on measurements of a thermocouple placed as close to the LED as possible. Further explanations about thermal aspects will be given in the next section. Optical experimental results are shown in Fig 4.

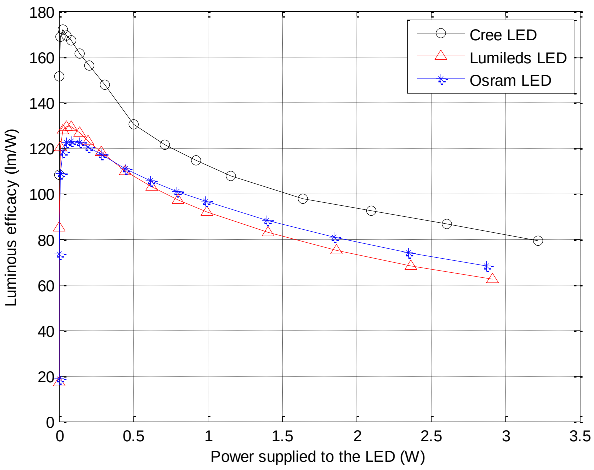

Fig. 4. Luminous efficacy vs. Power for the three tested LEDs

It can be noted that the forward current used to supply an LED has a strong impact on the luminous efficacy. In Fig. 4, for each type of LED, currents between 50 mA and 100 mA lead to the best luminous efficacy.

The number of LEDs noted N_{LED} required to have the 3600lm desired luminous flux, as previously stated, for a given supplied power P_{Led}, can be calculated:

$$N_{LED}(P_{Led}) = \frac{LF_d}{\eta_{Lum}(P_{Led}) \times P_{Led}} \tag{1}$$

where LF_d is the desired luminous flux, $\eta_{Lum}(P_{Led})$ is the luminous efficiency obtained for a given supplied power noted P_{Led}.

Obviously, the power of an LED luminaire is defined as:

$$P_{Lum} = N_{LED} \times P_{Led} \tag{2}$$

For each forward current, a LED string combination is calculated based on equations (1) and (2). In the actual context of low consumption electric appliances, the consumption of the LED luminaire has to be taken into account. The different combinations are plotted in Fig. 5. As stated before, forward currents below 50 mA have been removed from this plot because thousands LEDs were necessary to obtain a luminous flux of 3600 lm.

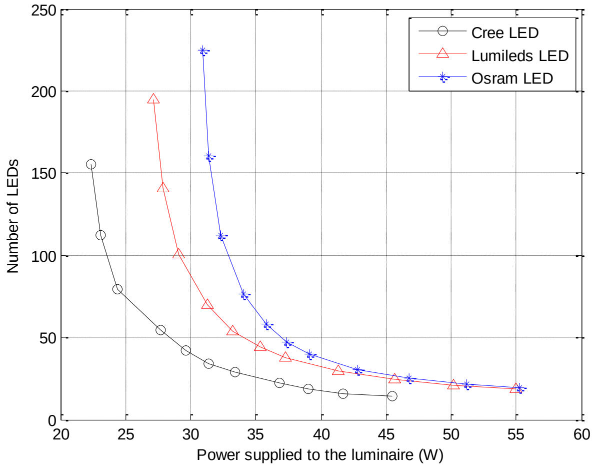

Fig. 5. Luminous efficacy vs. Power for the three tested LEDs

The next section is focused on the influence of the forward current on the junction temperature of the LED. Indeed, the junction temperature affects the luminous flux and lifetime of an LED [5-9].

IV. THERMAL MODELING OF AN LED

As any P-N junction, the junction temperature of an LED is heating when supplied. Many models are available to accurately represent the thermal behavior of an LED such as the Shockley equation [24-25]. In this paper, a simplified steady state thermal model is derived from [7]. The variables of this model are represented in Fig. 6.

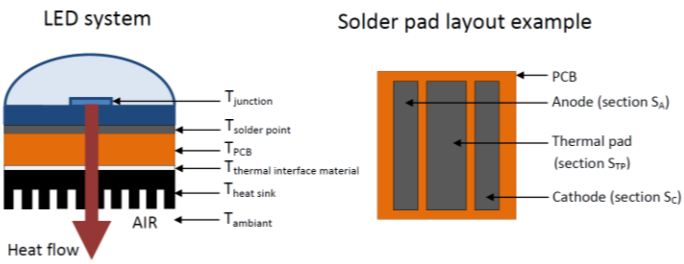

Fig. 6. Thermal variables used to model an LED system

An LED luminaire can be modeled with a simple resistor network to define a static thermal model as illustrated in Fig. 7.

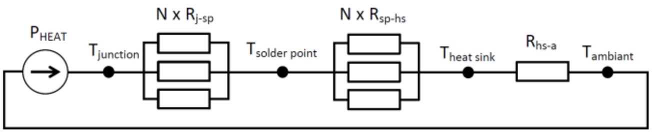

Fig. 7. Thermal model of an LED

The junction temperature is difficult to measure and can be estimated by using a thermocouple placed as close as possible to the LED. The temperature measured by this thermocouple is called the solder point temperature.

Based on the static thermal model presented in Fig. 7, the temperature of the solder point can be predicted for each forward current. Thus, if N_{LED} LEDs are mounted on the same heatsink, the temperature of the solder point can be computed with the following relation derived from Fourier's law of heat conduction:

$$T_{sp} = T_a + \left(\frac{1}{N_{LED}} R_{sp-hs} + R_{hs-a}\right) P_{heat} \quad (3)$$

where

T_{sp} is the temperature of the solder point (°C)

T_a is the ambient temperature (°C)

N_{LED} is the number of LEDs mounted on the same heatsink.

R_{sp-hs} is the thermal resistance between the solder point and the heatsink (°C/W)

R_{hs-a} is the thermal resistance between the heatsink and ambient (°C/W)

P_{heat} is the amount of input power converted by the LED as heat (W)

P_{heat} is calculated as follows:

$$P_{heat} = \eta_{heat}\, N_{LED}\, V_f\, I_f \quad (4)$$

with

η_{heat} the non-efficiency of an LED, it describes the amount of heat converted from input power. As described in [26], η_{heat}=0.85 is considered

V_f and I_f are respectively the forward voltage (V) and the forward current (A) of a single LED.

Thermal conductivity is generally used to define any PCB and thermal grease. R_{sp-hs} corresponds to the sum of PCB and thermal grease thermal resistances. Here is the relation between the thermal resistance R_x of a material and its thermal conductivity:

$$R_x = \frac{L}{k\,A} \quad (5)$$

with

L the thickness of the material x (mm)

k the conductivity of the material x (W/mK)

A the contact area between the heating device and the material x (mm²)

As previously mentioned, three strings of LEDs will be evaluated. Each string is constituted by three identical LEDs. LED strings have been powered separately in a 25°C temperature chamber with current pulses of 30 minutes from 50 mA to 700 mA with 50 mA increments. Rests of 30 minutes have been done between two pulses. In Fig. 8, the voltage of the string has been averaged to a single LED.

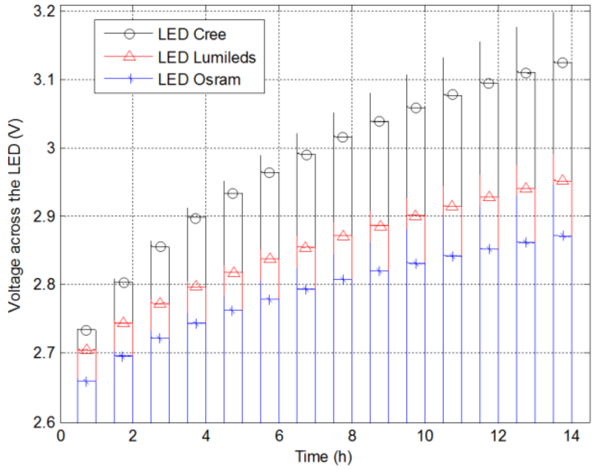

Fig. 8. Voltage across each LED for different forward currents

With the previous voltage measurements and a good estimation of R_{sp-hs}, it is possible to predict the temperature of the solder point by using equation (3).

The measured and modelled rise of LED solder point temperature is illustrated in Fig. 9. Only one temperature evolution has been plotted for LEDs from Cree and Lumileds because they have exactly the same temperature during all the experiment.

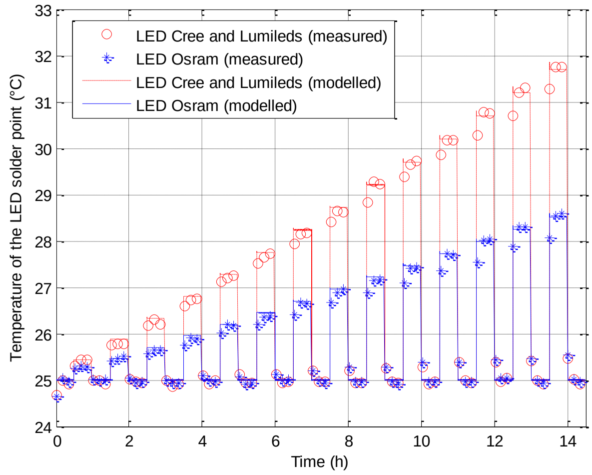

Fig. 9. Evolution of LED solder point temperatures

The temperature of the Osram LED is very low compared to the other LEDs. To have a model which well fits with data, an abnormal very low η_{heat} has been computed (η_{heat}=0.45).

To evaluate the junction temperature of the LED, there is a relation between the junction temperature and the solder point of an LED, defined as:

$$T_j = T_{sp} + R_{j-sp}\, P_{heat} \tag{6}$$

where

T_j is the junction temperature of the LED (°C)

R_{j-sp} is the thermal resistance of the LED between junction and solder point (°C/W)

Due to LED heating, according to our experiments, a drop of luminous flux occurs for every assessed current and can be limited to maximum 10% if the junction temperature stays below 80°C. In this case, the drop of luminous flux can be neglected because it is not visible for the common human eye [27]. As a consequence, it has been chosen to discard the results given by the Pareto optimization if the junction temperature is higher than 80°C. The same observation has been made concerning the drop of voltage across a heating LED, phenomenon which is also neglected because it does not have a significant impact on the LED junction temperature prediction.

The next section presents how to estimate the ageing of a LED in function of its junction temperature.

V. LED AGEING MODEL

The study of LED ageing, also called lumen maintenance, is determined by its lumen depreciation. The lifetime of an LED is defined by the number of operating hours before the luminous flux decreases below 70% of its initial value. This lifetime is often noted L70. According to the Illuminating Engineering Society of North America (IESNA), the standard TM 21 provides a method to assess the lumen maintenance of LEDs.

A simplified model of lifetime has been computed based on [27] as illustrated in Fig 10. In this model, it is assumed that the ageing of the LED is related to the junction temperature. For warmer junction temperatures, an LED operates less hours. Furthermore, two forward currents have been represented because the lifetime also depends on this parameter. As it is a simplified model, it will be considered that currents below 350 mA have the 350 mA behaviour, whereas higher currents will follow the 700 mA ageing model.

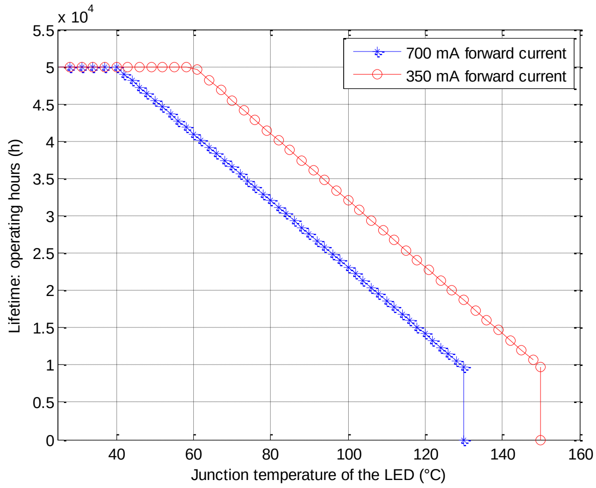

Fig. 10. Simplified lifetime model of an LED [26]

It is important to define an equivalent period depending on the junction temperature: for example in Fig. 10, the LED can operate up to 50,000 hours for a junction temperature of 40°C but it can only operate 10,000 hours if the forward current is 700 mA and the junction temperature is 120°C. A simple way to take this into account is to consider that the LED is working 5 times more at 120°C than at 40°C. Considering a factor noted α enables to count the equivalent operating hours of LEDs for different junction temperatures and forward currents:

$$\alpha = \frac{t_{op}(25°C, I_f)}{Lifetime(T_{jLED}, I_f)} \tag{7}$$

where

$t_{op}(25°C, I_f)$ is the operating lifetime of an LED at 25°C for a given current (hours)

$Lifetime(T_{jLED}, I_f)$ is the number of hours given by the LED lifetime model for given junction temperatures and currents (hours), as described in Fig. 11.

As defined earlier, the lighting mission profile is close to a shopping center: 12 hours a day, 6 days per week and 52 weeks per year, it represents 74 880 hours of lighting over 20 years. The number of replacements over 20 years, noted N_{repl} can be calculated:

$$N_{repl} = \frac{\alpha \times T_{ON}}{t_{op}(25°C, I_f)} \tag{8}$$

with

T_{ON} the number of operating hours over 20 years (hours)

Once luminous, thermal and ageing behaviour of LED have been discussed, the cost analysis of the luminaire needs to be developed. This model and the results of the methodology will be given in the next section.

VI. LED LUMINAIRE COST ANALYSIS AND RESULTS OF THE METHOD

The cost analysis of the LED luminaire will be done over a period of 20 years. Assuming that the power converter associated to each luminaire configuration have roughly the same price, this cost will not be taken into account in the model because it will have no influence on the final comparison. In order to evaluate more solutions, three different heatsinks will be assessed for each forward current. As illustrated in Fig. 5, the luminaire will need a power supply comprised between 20 W and 60 W so heatsinks with a thermal resistance of 0.4 K/W, 1.2 K/W and 2 K/W have been selected. An additional cost per LED has been computed respectively corresponding to 0.6 €, 0.35 € and 0.2 €. This cost is based on the cost of large heatsinks (200 x 200 x 25 mm).

The following formula is often used in renewable power projects like in [28, 29] and well-known under the name of levelized cost of energy. It has been adapted to lighting systems for this study in order to calculate the luminaire annualized cost LAC (€/operating hour):

$$LAC = \frac{\left(C_{Lighting} + C_{repl}\right) F + C_{O\&M}}{T_{ON\ yearly}} \tag{9}$$

with

$C_{Lighting}$ the initial capital cost of the luminaire corresponding to the cost of LEDs and heatsink (€)

C_{repl} the replacement cost of LEDs over 20 years (€)

$C_{O\&M}$ the annual cost of maintenance (€), consider 50 € per luminaire

$T_{ON\ yearly}$ the number of operating hours per year (hours)

F the capital recovery factor, F=0.0802 for this project. It is defined as in [28 - 30]:

$$F = \frac{i_a(1 + i_a)^x}{(1 + i_a)^x - 1} \tag{10}$$

where

i_a is the discount rate, considered equal to 5% for a project of 20 years

x is the duration of the project (years)

The LED model is now completed. It is possible to evaluate each LED luminaire configuration over 20 years of operation subject to its annualized cost and energy consumption as described in Fig. 2.

Three Pareto fronts are obtained, as illustrated in Fig. 11. In Fig. 11, D1, D2 and D3 designate respectively heatsinks with thermal resistance of 0.4 K/W, 1.2 K/W and 2 K/W.

It is to notice that for each type of LED, an inversion occurs which means that the heatsink which leads to the optimal luminaire for low power does not lead to the optimal luminaire for high power. This inversion occurs when the lifetime model switches from the 350 mA ageing curve to the 700 mA curve.

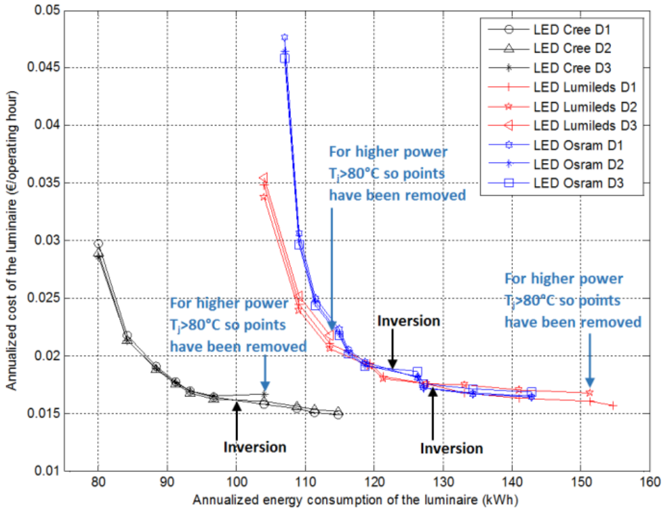

Fig. 11. Annualized cost vs. power of the luminaire

Some points have been removed from the Fig. 11 because the junction temperature of the LED reached 80°C which means that the luminous flux will decrease over 10% from its nominal value: these solutions are not acceptable. Currents below 50 mA have also been removed because these configurations are not optimal: they lead to an expensive annualized cost and an annualized energy consumption which is greater than the energy consumption induced by the 50 mA or 100 mA forward currents configurations.

Forward currents from 50 mA to 700 mA are optimal in Pareto sense. For higher currents, the annualized cost of the luminaire is cheaper because the number of LEDs is smaller but the annualized energy consumption is bigger. The final user has to make a trade-off between buying a cheaper luminaire or making energy consumption savings. Some heatsinks lead to more optimal solutions but care should be taken with these results because this methodology is very sensitive to the ageing model of the LED. In other words, the LED ageing model needs to be very accurate to avoid any misleading interpretation.

VII. CONCLUSION

A methodology to find the optimal forward current of an LED luminaire has been proposed. It takes into account the luminous efficacy, the junction temperature modeling, the lifetime prediction and different costs associated to a LED luminaire.

Even if this method is very sensitive to the lifetime model, it appears that, for the three tested and simulated LEDs with different heatsinks, forward currents between 50 mA and 700 mA lead to optimal combinations of annualized cost and annualized energy consumption of the luminaire.

Due to the modularity of this methodology, LED models used in this method can be improved or adapted to any type of

LEDs. Other models may be added to improve the relevance of this methodology: reliability of the LED configuration (string, series string, series-parallel string modules), life cycle assessment (LCA), impact of current waveform on the behaviour of LEDs, design of DC/DC converters…

ACKNOWLEDGMENT

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