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ECOLOGICAL AND ECONOMICAL CONSIDERATION FOR TOMORROW'S CABIN LIGHTING IN AIRCRAFT

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Abstract

The idea behind general cabin illumination in today's and tomorrow's passenger aircraft is changing in many ways. First of all the aspect of passenger comfort is attending increasing attention especially for long range flights to support the mood and the biorhythm of the passenger in order to create a pleasant atmosphere during the flight. In addition to that Mood-lighting can support branding aspects for the airlines to extend their corporate identity into the cabin. Last but not least lighting can be used during the design of the cabin to shape the look-a-like of the interior. This trend actually started of in the beginning of this decade and currently peaks in the highly sophisticated lighting systems to be installed in the Boeing 787 and the Airbus A350XWB driven technically by the development of light-emitting diodes as modern solid state lighting technology being able to fulfil and support the design demands.

In addition to the trend for ambience lighting a second movement can be recognized most recently. Driven by the need to reduce the carbon footprint of air transport the aircraft fleets currently see urgent needs to accelerate the introduction of ecological systems and technologies to reduce energy consumption. Within this contribution Diehl Aerospace will show how such a lighting system can be designed given today's technology base and forecasting on future improvements. Accordingly the major technical challenges that need to be tackled and overcome will be revealed and discussed. Also additional different technical aspects like - among others - optical placement, installation and electronics will be addressed in order to show that such a solution cannot be based on one single improvement but is an inter-play between various effects.

1. INTRODUCTION

This contribution focuses on cabin lighting systems for aircraft used for passenger transport. The influence of the current technology development as well as the need to lower carbon footprint on the cabin lighting system will be discussed from today's standpoint and a prognosis for the future based on a specific mission scenario – namely lighting as basic illumination on short-haul flights - is given based on the relevant technological forecast.

Therefore this article is structured as follows: In chapter 2 today's state-of-the-art is introduced and explained as basis for the article. It will be shown that today's situation suggests that the two technologies introduced there – fluorescence based lighting and solid state based lighting by means of light-emitting diodes (referred to as: "LED" in the following") can support different requirement specification and can almost been seen as complementary in terms of usage profile. In the chapter following thereafter those different technologies are explained on a more technical basis together with the specific mission profile, i.e. the target aircraft service, chosen for this contribution. Here the metrology of cots of ownership calculations (CoO) used in the framework of this contribution is presented. Then the technological outlook for LED technologies is given in chapter 4 again based on the specific underlying mission scenario and benchmarked against the present technology level by means of cost of ownership calculations. This reflects the potential influence of foreseeable technological improvements on CoO calculation and thus the dependencies of the total system on certain technical parameters are pointed out. In the last two chapters the limitations of the model are revealed and discussed and conclusions on the results are made. Finally in the last chapter, the outcome is summarized in the last chapter.

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2. STATE-OF-THE-ART

Until a decade back virtually every aircraft was equipped with a lighting systems based on fluorescent tube technology, despite of its utilization profile (i.e. short-, medium-, or long-haul flights). This fact was based on the – at this time – unbeaten performance level fluorescence technology could offer. Nevertheless at this time a need for adopting the lighting systems towards the utilization of the specific aircraft, this is to say the so called 'mission profile', raised. Especially for long-haul flights a higher performance in flexibility and functionality was desired. Generally this trend is addressed as Mood-Lighting were basic illumination functionality is topped with abilities to create special illumination scenarios like coloured light and dynamic lighting scenes. Due to the limited technical possibilities solutions like using a dual-tube installation where one is coloured were introduced. Following soon LEDs were introduced as possibility to generate Mood-Light scenarios whereas the basic white light was still generated using fluorescent tubes. This technology step is called 'Hybrid-technology". Recently LED performance obtained a level sufficient to generate also the white light and thus the lighting systems to be installed in the soon-to-sell Airbus A350XWB and Boeing 787 models will be based fully on LEDs [1]. This evolution followed nicely a classical market introduction from niche applications making use of the unique features towards a general use when the technology is mature. However, even if the above explanation might suggest that LED technology has squeezed fluorescent technology out of the market it is only true for aircraft having mission profiles in the long-haul segment. Here the requirement levels for the lighting systems because of the desired Mood-Light abilities clearly bring LEDs into the leading position.

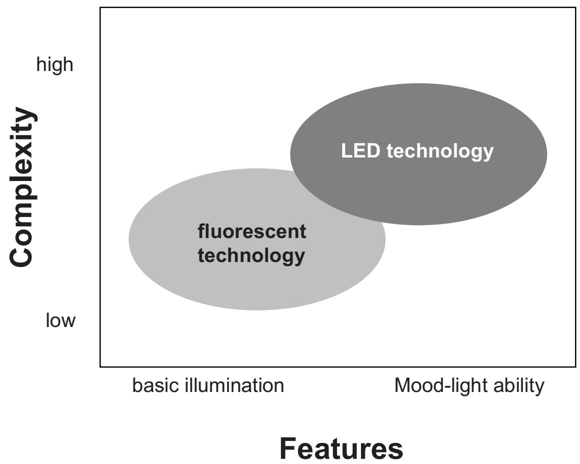

Fig.: 1. The classification of the recent situation regarding performance vs. complexity is shown. LED technology is used for feature-rich installation resulting in a higher complexity level whereas fluorescent technology is used for basic illumination purposes

Accordingly the situation changes if analysing the segment of short-haul flights where the need for Mood-Lighting is far less expressive. Here performance issues related to the basic illumination function are in the forefront. In that sense here LEDs need to undergo a replacement competition with the well established fluorescent technology. This illustrates why nowadays still most aircraft in this segment are equipped at aircraft OEM level – or have been equipped until very recently - with fluorescent technology.

Generally, the marketplace can be divided into performance-wise fragmented segments making use of specific technologies complementing each other and having little overlap. This situation is indicated in Figure 1. The main reason for fluorescent technology still being competitive in the low-feature region is rather easy to assess: The efficiency values (in terms of power to light conversion) of both technologies are in first instance close to each other. LEDs as semiconductor devices are more complex to drive by means of controlling electronics but offer much more freedom in operation and longer lifetime. So whenever the higher freedom of operation is needed and is paid off LEDs are in the lead. As soon as it comes down to simplicity fluorescent technology was the offer of choice. Following that explanation and having in mind that only a rather superficial argumentation was given here the actual situation regarding the benchmark of LEDs and fluorescent technology is assessed and discussed in detail in the following chapter now solely based on a situation where basic illumination is key.

3. SITUATION FOR SHORT-HAUL AIRCRAFT

In above chapters much of the explanation was based on the fact that different aircraft are designed to operate under different operation profiles. Classically one could separate passenger aircrafts into commuter and regional planes were some dozen passengers are transported e.g. from a smaller airport to a larger one in order to have the passengers getting a connection flight or to stay there. The second class would cover flights connecting two airports (e.g. intra-European) with typically 1-3 h flight-time typically in such a high frequency that planes with a capacity of less than 200 passengers are sufficient. The third segment would cover flights of 7 hours an more mainly connecting major airports - most likely on different continents [2] [3] [4] [5]. The aircrafts used for these segments can be identified either via seat capacity and/or maximum range. One exception of this classification might be found in charter-flights where smaller aircraft are used on longer. However this segment seems to influence the overall aircraft design only in minor ways and is thus not considered any further in this context.

For the purpose of this article it is proposed to further simplify the classification into two segments only: flights up to 4 h max, where the need for Mood-Lighting is evanescent and in contrast to that flights with more than 7 hours flight duration where Mood-lighting is a common feature. As in the latter segment the market is already dominated by LED this article will concentrate on the class of flights shorter than 4 h.

To access which of the two mentioned technologies – fluorescent or LED – allows for most effective operation a cost of ownership calculation was used. In Figure 2 the results of the traditional fluorescent system are used to introduce the CoO presentation. Using the CoO model the total operational costs can be divided in two major parts where one reflects the direct operational costs (greys in Figure 2) related to fuel consumed to operate the system whereas the other one shows the maintenance costs (dashed in Figure 2). The costs for depreciation or provisions e.g. recycling are not taken into account as they do not impact the ecological considerations and must undergo a different assessment in terms of analysis than shown here [6] [7]. In Figure 2 the direct operational costs are further divided into sub-parts reflecting the primary operation costs resulting from the power consumption (light-grey) and the secondary operation cost resulting from carrying the weight of the system (dark-grey). The effort to carry the weight of the fuel needed to produce the power is seen as part of the power consumption. This split reflects the two major improvement factors either lower weight or lower power consumption and their respective effect on the total. Starting from the early 1940s fluorescence tubes were used for aircraft illumination at an efficiency level of 20 – 30 lm/W [8]. However it is a known fact that the development of fluorescence tube is quite mature nowadays and therefore today's efficiency level of 90 - 100 lm/W – excluding driving electronics – seems to be the final stage [9]. The maintenance cost in case of the presented fluorescent system consists of two major parts again: On the one hand exchange of electronic parts e.g. according to standard mean-time-to-failure driven occurrences and on the other hand the quite frequent exchange of the tubes either standardized in scheduled intervals or by accident if a tube fails suddenly.

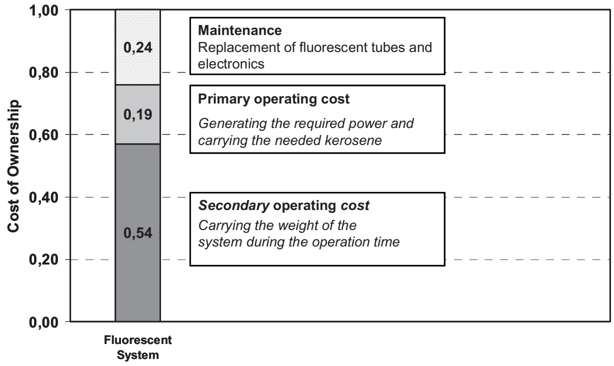

Fig.: 2. Normalized contributions to the total operating cost as labelled and explained in the graphic. The calculation is based on a tube efficiency of 90 lm/W.

It can be noted that Figure 2 only shows a snapshot on the actual relations as the operating cost are closely related to the fuel price. Today's price level suggests a regime of 100 – 150 $/kg and year; however as the oil price is highly volatile this figure will change [10]. The driving forces behind the maintenance are on the one hand the labour costs and on the other hand the cost for spare parts, thus being much less affected in the short term.

4. LED BASED SYSTEMS ON SHORT-HAUL AIRCRAFT

To access the potential of a LED based solution for that segment a LED system was designed virtually in order to freely change substantial performance parameters and monitor the resulting influence on the overall system. The prime premise for the virtual concept of the LED based system was to keep the overall light output comparable to the fluorescent solution – thus targeting a similar performance level. Nevertheless when talking about efficiency values of LEDs one must keep in mind that the values reported often correspond to idealized driving conditions being different to those present in an aircraft – as indicated in Figure 3. Furthermore LED devices have different intrinsic radiation pattern compared to fluorescent tubes. The latter emit light evenly distributed in all directions along the tube-line whereas LEDs emit into a cone of a certain angle.

That means if a brightness level at a certain level or spot in the cabin is required LED light can be directed right there easily by nature therefore having a high usage of the overall produced light.

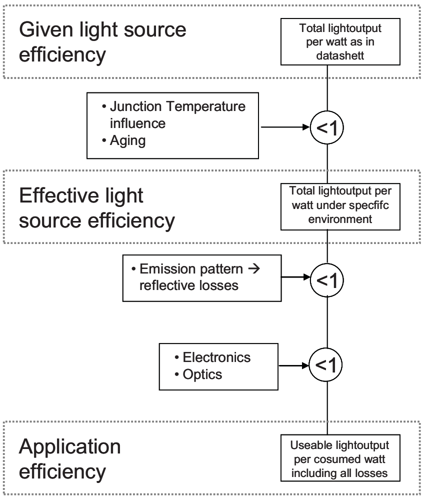

Fig.: 3. Efficiency flow from datasheet values to consumed power and used light.

In contrast the light of a fluorescent tube can not shine all its light on the desired region without redirecting major parts. Additionally in both cases the geometric design might give need to install optics to spread the light in a desired manner. Those facts – together with the knowledge that each driving electronic has a limited efficiency and thus produces electronic losses as well - gives rise to introduce the so-called *"application efficiency"* – benchmarking only the light that can be used by the overall power needed. The notation chosen with regard to efficiency in the context of this article is displayed in Figure 3. For clarity reasons and comparability this article references efficiency values always as the "given light source efficiency" to allow benchmark with standard datasheets (refer to [9], [11]).

Going through the efficiency flow as given in Figure 3 one end up with the conclusion that a LED system needs to emit – at maximum - only about 80% of the total light output compared to a tube system to reach the same application efficiency considering optimised installations for each of the two technologies as well as all electronic loses. Keeping this in mind a virtual benchmark LED system can be constructed by exchanging the electronics and the tube of the fluorescent system with the amount of LEDs and the electronics needed. With regard to the driving electronics, common features known from the existing Mood-light LED systems like compensation of temperature- or aging dependent emission changes of the LED are still considered to be included in terms of weight and power consumption. Thus the optical performance of the system is made constant over time by electronic balancing. However the underlying change in LED performance needs to be reflected in the operation considerations as fresh LEDs need less power than aged ones. [11]. To account for those changes mean efficiency values are used in the CoO while the initial efficiency values are stated in the following.

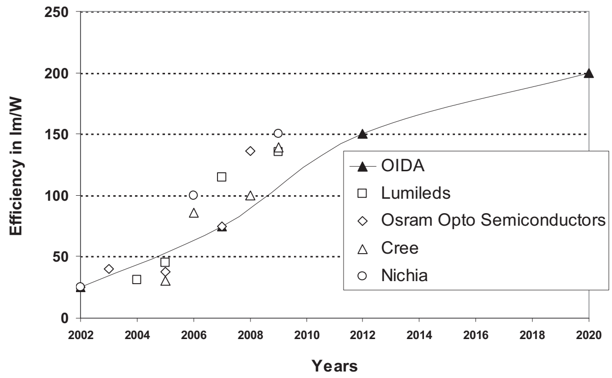

Fig.: 4. LED efficiency forecast values as given in the OIDA report 2002 along with some published results by the major LED manufacturers. The forecast values even stay below the reported results [13] [14] [15] [16].

The most prominent technological influence on the direct operating costs of the LED based system is the efficiency of the LED itself. Over the last years the efficiency values increased in large steps ramping up to values reported as 100 lm/W and even more. In Figure 4 the values from the 2002 OIDA[2] forecast are given together as well as some efficiency values recently published by different LED manufactures. As it can be seen in 2002 OIDA forecasted an efficiency of 75 lm/W in 2007 whereas actual values exceeded 100 lm/W [12] The increase in efficiency is not scheduled to stop within the next years and actual trends as well as forecasts give hope that efficiencies surpassing 150 lm/W will become available soon [17] In Figure 5 a benchmark of the fluorescent system as introduced above against a virtual LED system is given. Here the LED system is 'composed' in a way that both CoO calculations were trimmed to result in the identical total sum using the LED efficiency as variable parameter. In such way the 'break-even' performance of the LED can be estimated. In Figure 5 it can be noted that if the overall cost of both systems are forced to be similar the cost portions show a different structure: Due to the longer lifetime of the LEDs and thus a less frequent need for exchange the maintenance cost are lower than in the case of the fluorescent system. Because of the nature of this calculation the benefit is compensated by the cost for weight and power defining the lower limit for the LED efficiency to 90 lm/W at a – preset – lifetime of 50.000 h. It can be seen in Fig. 5 that the LED based system has a higher power usage than the fluorescent because the effective light source efficiency (see Figure 3) of the LED is lower compared to its nominal value. In contrast to that, the effective efficiency of the fluorescent light stays unaltered compared to its nominal (given) light source efficiency.

[2] OIDA: Optoelectronics Industry Development Association

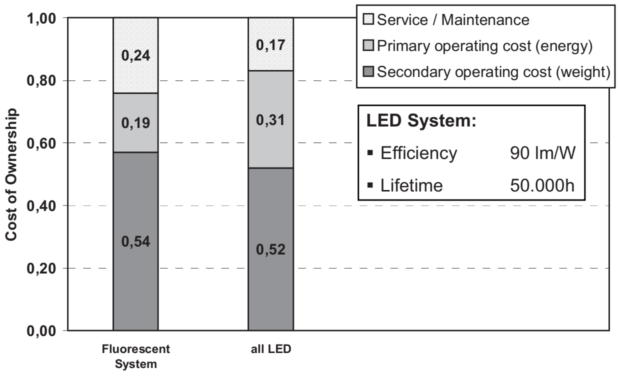

Fig.: 5. Comparison of CoO structure of fluorescent and LED based systems. The overall costs were set equal by default for this calculation to emphasize the differences in the cost structure and calculate the 'break-even' performance of the LEDs – see inset.

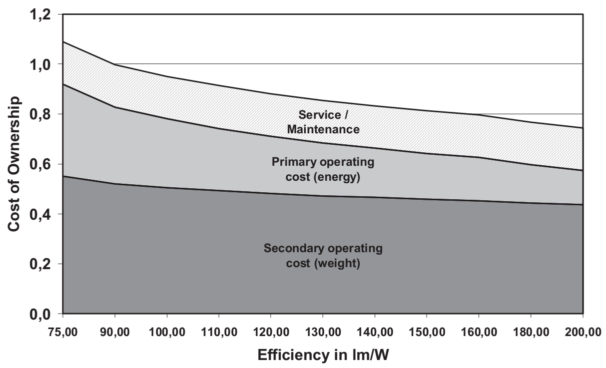

Fig.: 6. Dependency of the CoO on the LED efficiency. The primary operating costs halve with doubling efficiency. Additional benefits arise out of the weight reduction due to the higher efficiency.

The split between the primary and secondary operation cost as shown in Figure 5 is only one of the possible embodiments as the ratio represents a trade-off between effective efficiency - affecting primary operation costs - and weight of the cooling provisions - affected the secondary operation costs.

Any larger change in the aircraft power system structure e.g. using a smaller and less heavy generator if less power is needed however is not taken into account. Typically such major changes in overall set up won't result from savings in the lighting system alone. Here other topics like effective power management and/or intelligent power distribution might be determining factors.

Figure 5 is based on technological factors like LED performance as well as on economical factors - mainly fuel price - and is in first instance only valid in this specific context. To address potential variations and highlight the future potential the key influences – namely LED efficiency, LED lifetime and fuel price – are now discussed step-by-step in the following.

LED EFFICIENCY

The strongest and also the most obvious parameter that changes the situation is the efficiency of the LED. It has two kinds of impact on the system performance. Firstly a higher LED efficiency lowers the power consumption. Secondly a higher power-to-light conversion rate also implies a lower waste-heat production and therefore a lower need for cooling provisions. This ends up in lower weight of the system. This 'snowball effect' results in a superlinear dependency of the systems performance on the efficiency. As the future remains unknown the extrapolation of the efficiency is based on the OIDA forecast as introduced earlier.

In Figure 6 the dependency of the CoO of the LED system is shown up to a given light source efficiency of 200 lm/W with lifetime kept constant. For clarity reason the normalization is similar to Figure 2. As it can be seen the overall costs go down by more than 25% if the efficiency of the LEDs is increased from 90 lm/W to 200 lm/W.

LED LIFETIME

The maintenance costs of the system are primarily a result of the lifetime of the light sources as well as the other electronic parts. In the case of the fluorescent system the light source is separated from the rest of the system to allow easy exchange because of the very limited lifetime of the tube. In case of LEDs the lifetime is in an order of magnitude that a frequent exchange is not foreseen. Here the light source can become an intrinsic part of the light fixture. However to further reduce maintenance cost an extended lifetime is key as the LED lifetime adds up to the variable part of the maintenance cost. As it can be seen in Figure 7 an increase of lifetime of the LEDs from 50.000 to 100.000 h has minor influence on the total costs. This is because the LEDs keep running throughout a large fraction of the planes life and only faulty parts need to be exchanged. When the lifetime is enhanced even further reaching 200.000 to 300.000 h the probability to fail becomes smaller and smaller. The socket seen for the maintenance costs in Figure 7 relates to all surrounding equipment other than the LEDs. However the remaining electronic components haven't been considered as influence-able in the context of this article.

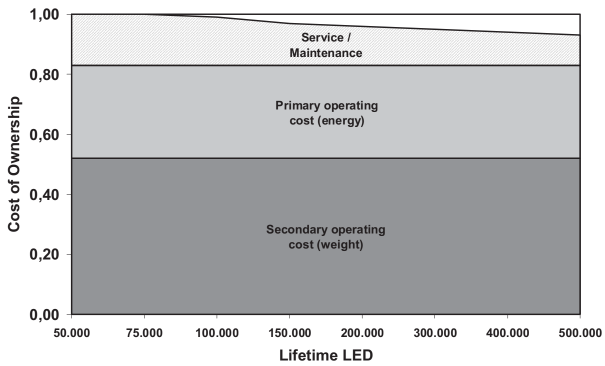

Fig.: 7. Influence of the LED lifetime on the CoO.

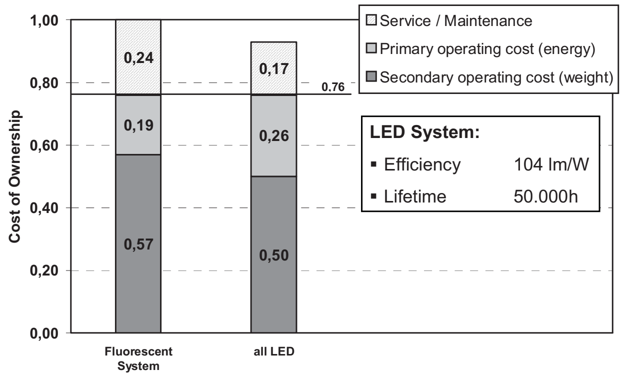

Fig.: 8. 'Second break-even' configuration having identical fuel related cost fraction. The resulting LED efficiency is given in the inset.

FUEL PRICE

Another quite important aspect to cover here is the fuel price as a technical solution should not only be superior at a certain set of - changing – parameters but should allow a choice independently especially of the most volatile cost factors as fuel. As pointed out above all CoO calculations shown so far were based on a certain fuel price level – namely of June 2009. However the oil price and therefore the cost of fuel are strongly volatile and are expected to increase in the future. This gives rise to design a LED based system that has a superior CoO structure compared to a fluorescent system independent from the future fuel price developments. In above sections it was pointed out that operational costs are strongly dependent on the fuel price whereas the maintenance costs are linked only indirectly and very weakly. Therefore a system superior independently of the fuel price must have not only an overall cost advantage but must also be competitive if only the operational costs are assessed. This requires to define a 'second break-even' LED efficiency. At this level of performance the effort to operate and carry the lighting system is similar to a fluorescent system and therefore the relationship does no longer depend on the fuel price in any means - – even if the lower maintenance cost suggest cost advantage earlier. In Figure 8 this situation was analysed again via CoO calculating LED efficiency as a result by keeping the operational costs – primary plus secondary – fixed and equal to those of the fluorescent system. Here it can be demonstrated that with an efficiency of 104 lm/W the break even also in operational cost structure is reached and from this value on LED systems are equal or superior performing under all external conditions.

5. LIMITATIONS OF THE MODEL

However in the considerations in the context of this contribution certain assumptions were made. Generally speaking one the one hand all installation and integration aspects were assumed to be optimised to minimize potential loss mechanisms that are irrelevant for the technological benchmark on the other hand optical influences like production related variations of the LEDs in colour were not considered. Therefore if translating the results into real devices some additional challenges will arise. Among others but being rather prominent is the installation of the light fixtures within the cabin interior were much light can be lost due to e.g. shading effects or undesired reflections. This influence can play a key role how well a lighting system installation performs in the end but was set in the context of this more generally accessing contribution as not influencing the situation. Also to be addressed are optical effects that might change a real world configuration as well for instance the density of LEDs on the PCB – e.g. fewer high power LEDs vs. a larger amount in the mid-power range – will influence the homogeneity in terms of brightness leading to requirements towards the LED configuration depending on the installation. Another well known effect in this context is that LEDs parameter underlie certain distributions in electrical as well as in emission characteristics. The LED manufactures typically sell LEDs in so-called bins containing LEDs being grouped within specific performance boundaries but showing a certain statistical distribution within those values. Those variations can lead to an inhomogeneous brightness and or colour distribution that - under certain conditions - can recognized by the human eye. Furthermore inhomogeneous emission can also occur as result of differential aging of the LEDs during operation. Therefore additional electronic compensation mechanisms are needed which are affecting weight and power consumption of the installation. Those mechanisms are also used in the feature-rich Mood-Lighting systems. Besides that but to be mentioned as well is the unchanged mechanical design used in the calculations shown in this article. That design was not correlated or changed in any means with regard to the increased performance of the LEDs. In reality that could open up additional room for improvement and therefore could reduce the CoO of LED based systems compared to the results shown here.

In our opinion all these facts are very important to consider and to address during realization of a LED based lighting system. However in the framework of a generalized consideration about an assessment of first instance performance entry barriers they should not be considered as ruling facts. Nevertheless such considerations might either increase performance threshold values if not tackled in the right way or might cause unsatisfying results in terms of optical appearance.

6. CONCLUSION

It is the aim of this contribution to access the best possible technology for short-haul aircraft cabin lighting. As it has been shown the most powerful tool for such consideration lays in a cost of ownership calculation that is not only used to reveal the actual status but also to forecast impacts based on input parameters taken out of technical roadmaps.

The economic focus of the considerations was put on the market segment were basic illumination by high quality white light is needed without any major needs for features like Mood-Lighting. This segment reflects flights in the range of maximum 4 h with aircraft having capacities smaller than 200 passengers. In order to do so, the existing system – fluorescent based – was benchmarked from a technical standpoint against a virtual LED system. For the LED system the major technical input parameters were varied in order to access situations were both systems behave equally and thus used to extract technical threshold values for LED systems. In the beginning a ‘first break-even’ efficiency was calculated in order to access a situation with both systems having identical overall costs no matter how these costs are distributed over the different factors. As in that calculation the fuel price needs to be set to a specific value – e.g. as of today – the result is dependent of an unpredictable economical variable which by different setting even changes the overall result. However as the fuel prices are commonly expected to increase in the future this value can be used as minimum border where a beneficial introduction of LED systems is feasible. To generalize the result and to make it independent of economic issues a ‘second break-even’ efficiency was introduced. This second value resembles the efficiency value were the two technologies behave identical in all fuel dependent cost fractions. It can be noted that because of the generally lower maintenance cost of an LED based system this value can be regarded as upper limit for LED systems to be superior in any case. The calculations revealed that those two efficiency values, being 90 lm/W and 104 lm/W respectively are quite close and moreover are within the predicted efficiency range of the LED makers – at least for cold whites - following the information on recent efficiency values as well as according to accessible performance roadmaps. In general one can conclude that today’s circumstances suggest a head-to-head situation in terms of performance. However, knowing that the LED technology being developed further quite rapidly this state of equilibrium remains only a snapshot in time. Without doubt it can be concluded that by time LED solutions will become more and more beneficial and will clearly outperform fluorescent based systems.

To confirm that CoOs will further drop in the future of the forecasted LED - guided again by the OIDA forecast - have been calculated in Figure 9 for comparison.

Here the CoOs for LEDs performance values as forecasted by OIDA are displayed (for the performance parameters taken please refer to the table in the inset of Fig. 9) being normalized to the performance level of 2009 and thus also comparable to fluorescent tube performance.

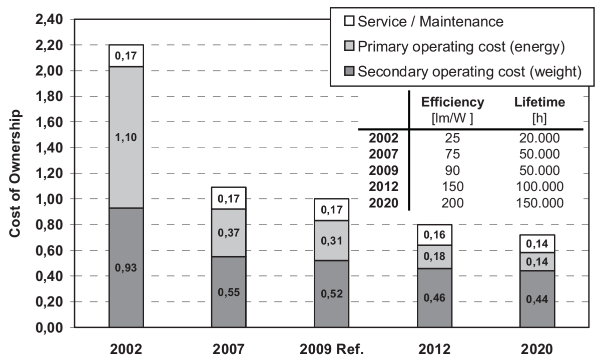

Fig.: 9. CoO structure and relation using the ‘OIDA’ forecasted LED performance values as of 2002 and the 2009 performance level as reference. The LED efficiency and lifetime data are given in the inset of the graph. All normalization factors are similar to Fig. 2.

7. SUMMARY

To sum up, with the calculations shown in this contribution it has been revealed that a LED based design of cabin lighting results in a competitive performance compared to existing fluorescent tube based installations as soon as a certain performance level is reached, mainly dominated by the LEDs' efficiency. As this level is calculated to be roughly 100 lm/W the potential should be accessible. Furthermore based on the prognoses of LED efficiency roadmaps it can be concluded that systems saving energy by means of less fuel consumed will become available soon. Those systems will on the one hand strengthen the competitiveness by better economics but on the other hand will also lead to increased ecological performance because of – again – less fuel burned as well as lower efforts to recycle fluorescent tubes with all its implications.

8. ACKNOWLEDGEMENT

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[1] http://www.diehl-aerospace.de/index.php?id=1402, seen June 22nd 2009
[2] Airbus S.A.S., Demand for passenger aircraft, Global market forecast 2007 - 2026, 2007, page 53 -109
[3] Boeing Commercial Airplanes, Current Market Outlook 2008 - 2027, 2008
[4] Bombardier Aerospace Commercial, Bombardier Commercial Aircraft Market Forecast 2009 – 2028, 2009
[5] Embraer Commercial Jets, Embraer Market Outlook 2009–2028, 2009
[6] Scholz D., DOCsys - A Method to Evaluate Aircraft Systems. In: SCHMITT, Dieter (Ed.): Bewertung von Flugzeugen (Workshop: DGLR Fachausschuß S2 - Luftfahrtsysteme, München, 26./27. October 1998). Bonn : Deutsche Gesellschaft für Luft- und Raumfahrt, 1998
[7] Lemke J., Betriebskosten-berechnungen für Kabinensysteme, Workshop des DGLR-Fachbereichs T8 "Flugzeugbordsysteme" und des DGLR-Fachausschusses S2.1 "Starrflügelsysteme", Hamburg-Finkenwerder, 10./11. Mai 2001
[8] Philips Lighting, Price list 2008/2009, status 09/2008, pages 84 - 116
[9] Jenkins H. J., Fluorescent Lighting, Aircraft Engineering, April 1942
[10] Energy Information Administration, Amsterdam-Rotterdam-Antwerp (ARA) Kerosene-Type Jet Fuel Spot Price FOB, http://tonto.eia.doe.gov/dnav/pet/hist/rjetara5M.htm, seen June 22nd 2009
[11] Philips Lumileds Lighting Company, Technical Datasheet DS56, LUXEON Rebel, 2009
[12] Jeff Y. Tsao, Sandia National Laboratories, An OIDA technology roadmap update 2002, in: Light Emitting Diodes (LEDs) for General Illumination, October 2002
[13] Press Releases, http://www.philipslumileds.com/press/, seen June 22nd 2009
[14] Press Releases, http://www.osram.de/osram_de/Presse/Fachpresse, seen June 22nd 2009
[15] Press Releases, http://www.cree.com/press/pressreleases.asp, seen June 22nd 2009
[16] Press Releases, http://www.nichia.com/about_nichia/new.html, seen June 22nd 2009
[17] Press Releases, http://www.cree.com/press/press_detail.asp?i=1227101620851, seen June 22nd 2009