Published by journal 'Lighting Research & Technology'. Publisher: SAGE.
Article first published online: May 12, 2017. https://doi.org/10.1177/1477153517708597
Version of this file: post Version 2 (the accepted, peer-reviewed version), not Version 3 (the final, typeset PDF).

Article type:

Case study

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Article title:

Comparative Life Cycle Assessment of LED lighting products

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Abstract:

LED lighting products used in lighting applications and their subsequent environmental impact are growing rapidly. However, there are no in-depth updated studies that show how to assess and compare them for eco-design purposes. This research aims to add insights in this area to inform eco-design by assessing and comparing the environmental impact of a new LED eco-lighting product with an existing LED lighting product.

A cradle to grave Life Cycle Assessment (LCA) was conducted using ReCiPe Midpoint and Endpoint (H) life cycle impact assessment method with Simapro software. The system boundaries included all product life cycle stages, except the maintenance of the luminaires and the manufacturing of the packaging. A novel functional unit was defined for the assessment, which is more suitable for the LED lighting products. Six scenarios were considered, including three probable useful lives of the luminaires (1,000, 15,000 and 40,000 h) and two end of life options (domestic bin and recycling centre).

The LCA results revealed that the new eco-lighting product has about 60% less environmental impact than the existing lighting product in all scenarios. The life cycle stages with the highest environmental impact are: 1) Use, 2) Manufacturing, 3) End of Life and 4) Transport. Based on the results obtained, recommendations for eco-design of LED lighting products were proposed, and challenges of application of LCA for the eco-design were discussed.

Keywords:

Life Cycle Assessment (LCA), LED Lighting products, Environmental impact assessment, Light Emitting Diode (LED), Eco-design

1. Introduction

Further understanding about how to assess and compare the environmental impact caused by LED luminaires is necessary in order to reduce their impact on the environment. Despite the growing demand in LED-based lighting products, there are no studies that present an updated comprehensive comparative Life Cycle Assessment (LCA) study of LED luminaires to inform eco-designers on how to eco-improve a LED luminaire based on comparative LCA results.

There are a number of related existing studies (mainly aimed at LCA experts, not product designers), but they do not present an updated comprehensive comparative LCA to inform eco-designers, who need to assess and compare the environmental impact of two LED lighting products. Some of these studies, assessed and compared LED-based lighting products for street and general-ambient[1] lighting applications with non-LED-based luminaires. These studies used different light source technologies, such as Compact Fluorescent Light, in order to know which one had less environmental impact and in which life cycle stage the impact was allocated[2-7]. Tähkämö[8] assessed a single LED-based lighting product for general-ambient lighting applications, and UNETO[5] conducted a LCA of a LED luminaire, using eight different LED-modules, designed for general commercial lighting applications. All these studies differed in purpose, system boundaries applied, functional units, Life Cycle Impact Assessment (LCIA) methods used, and the scenarios assumed.

The existing studies used different LCIA methods, such as ECO-I-99[9], TRACI[10], ReCiPe[11], and ILCD 2011[12], and the results were shown using different damage and impact categories. The scope of these studies usually comprised a cradle to grave assessment, except a few, where some life cycle stages, such as transport[4,5] and end of life and packaging[5] were excluded.

For some of these studies, the researchers assumed certain scenarios. Tähkämö et al.[8] assumed scenarios based on two different luminaire useful lives (36,000 h and 15,000 h) and two different electricity mixes, French and European mixes. Principi and Fioretti[2] assumed scenarios based on two electricity mixes, European and Italian electricity mixes; and three end of lives, complete recycling, full disposal in landfill, and disposal in incinerator. Dale et al.[4] assumed scenarios based on three different electricity mixes, US average mix, regional mix, and 100% wind power. Abdul Hadi et al.[3] assumed two scenarios based on different electricity mixes, Photo Voltaic panels and solar power plant. Tähkämö and Halonen[7] assumed two scenarios based on two electricity mixes: European mix and Hydropower in Norway; two different data sources for LED modelling: US DOE and Ecoinvent; two LED efficiencies (97 lm/W and 200 lm/W) based on the current LED efficiencies, and a future scenario where LEDs will be more efficient.

Three different functional units were adopted in previous studies[2-4,7,8] including luminous flux (i.e. lm-h), luminance (i.e. cd/m^2-h), and illuminance (i.e. lux-h) produced by the luminaire. Luminous flux measures the perceived power of light, whereas luminance measures the luminous intensity per unit area, and illuminance measures the total luminous flux incident on a surface per unit area. Selecting the luminous flux as the functional unit allows measuring the light output from the source. Tähkämö et al.[8] selected a functional unit (1,140 lm-50,000 h), which is the luminous flux produced by the luminaire for a period of time equivalent to its useful life. Illuminance and luminance were used in some of the studies to define the functional unit[2,5].

Finally, there is one early study[13], which applied LCA to compare two LED lighting products as part of the demonstration of an incomplete design method to eco-design lighting products. However, this study did not explain the method followed to use the LCA tool to assess and compare LED lighting products in-depth, because the focus of the study was on the eco-design method, not on the detailed application of each eco-design tool (e.g. LCA) during the design process. In addition, the life cycle impact assessment method used in this LCA (i.e. EI-99) is out of date, and end of life and use scenarios were not considered.

This study aims to provide insights in the area of comparative LCA of LED luminaires to inform eco-design, building on the existing knowledge from previous studies in this field. In particular, it examines and defines the functional unit in detail, which is critical in this type of assessment, the ‘use’ stage-related scenarios, and the translation of the comparative LCA into eco-design recommendations for LED luminaires.

2. Life Cycle Assessment of the LED lighting products

The comparative study is conducted using two LED luminaires and their details are shown in section 2.1, the LCA is carried out using SimaPro V.8.2.3[14] software in line with LCA standards[15,16], and Ecoinvent V.3.2[17] is used as the database. Six scenarios are assumed in the assessment, one of which is used as the base-case scenario. The base-case scenario assumes that both luminaires are used for 40,000 h, distributed and disposed in domestic bins in the Netherlands. In the other five scenarios, different useful lives of the luminaire are assumed, and recycling in the end of life scenario is also considered.

SimaPro[14] is a leading LCA software package used to model and assess the environmental impact of products, processes or services. The underlying methodology used to model the environmental impact is based on LCA standards[15,16]. In order to conduct the assessment, all the materials and processes, i.e. Life Cycle Inventory (LCI) embodied in the product life cycle have to be input into the software. The LCI is then assessed using a particular Life Cycle Impact Assessment (LCIA) method (e.g. ReCiPe). The software allows choosing different LCIA methods according to user needs. Each of these LCIA methods interprets and assesses the LCI based on specific criteria and environmental impact indicators. After assessing the LCI with a LCIA method, quantitative results are presented based on different environmental impact indicators.

2.1 Introduction of the LED lighting products compared

This study focuses on the LCA of two LED-based indoor table lamps, L1 and L2 shown in Figure 1, both manufactured by Ona Product S.L.[18]. L1 is a standard luminaire that has been commercialised for several years, and L2 is a new spotlight eco-luminaire developed recently with the support of the European Commission's CIP Eco-innovation program[19]. L1 can provide ambient lighting, and L2 can provide ambient, task and accent lighting.

L2 presents the following features:

<u>Eco-features:</u>

- The casing is made of recycled PET, which avoids the use of virgin PET.
- A novel ad hoc inter-modules joint that allows several functions in one single part: the snap-fit joint allows full rotation of the modules whilst passing IP 44[20] and EC[21] safety tests; it also allows easy attachment-detachment of additional lighting modules. This joint allows light directional control, which means that light can be directed where needed, thus saving light and energy. It also allows the lighting product to ‘evolve’ according to users’ needs over time (e.g. more lighting modules can be added if the lighting needs change over time, which avoids to buy new lighting products), thus extending its lifespan. This joint also allows simplification of the casing manufacture, and reduces the number of parts to be manufactured to achieve the rotation function.
- A simple novel architecture of the product allows easy-fast access to components, and disassembly without the need of tools. This facilitates the repair and upgrade of components, thus extending the lifespan of the luminaire.

Lighting performance features:

- Full light control: Luminous intensity can be controlled with dimmers, and the light direction can be adjusted with the individual orientation of each lighting module, which can be rotated 360^o in horizontal and vertical directions. This allows usage of the exact amount of light needed where needed, thus saving light and energy.
- The luminous efficacy of the luminaire is 55 lm/W, which is a decent efficacy level. The Energy Star[22] label for luminaires recommends at least 50 lm/W for directional desk-luminaires. This is one of the main issues to take into account in the design of luminaires because the electricity consumed by the luminaire is usually the main contributor to the total environmental impact. Higher luminous efficacy means that the luminaire can produce higher light output with lower electricity consumption.

L1 is mainly made of virgin stainless steel and iron materials, and the parts that shape the structure are mostly welded. The light quantity and direction cannot be controlled as it has no dimmer or directional modules.

L1 uses one LED-lamp as light source, and L2 uses three LEDs, each of which is housed in an individual lighting module. L2 has a modular structure and can use up to four lighting modules; but in this study, the version with three modules is considered, which has the same input power as that of L1. The technical specifications of both luminaires are shown in Table 1, and the luminous intensity distribution curves are shown in Figure 2.

Fig.1. Luminaire 1 (L1) and Luminaire 2 (L2).

	L1	L2 (with 3 Lighting Modules/LEDs)
Weight (g)	4390	2133
Dimensions : x,y,z (cm)	41x44x10	45x72x19
Luminous flux of luminaire (lm)	102	948
Illuminance (lx) on luminaire's base	882	3825
Luminaire efficacy (lm/W)	15	55
Power consumption of luminaire (W)	6.7	17.2
Light Output Ratio (LOR)	0.3	0.9
Correlated Color Temperature (CCT) (K)	4000	4000
Color Rendering Index (CRI)	65	65
Luminous flux of light source (lm)	340	330 (1 LED module)
Light source efficacy (lm/W)	56	49
Light source useful life	40,000 h	50,000 h
Light source		LED: CitiLED - CLL010-0305A1-50KL1A1

	LED bulb: E-Core GLS 6W (neutral white)	
	Toshiba	Citizen

Table 1. Technical specifications of L1 and L2.

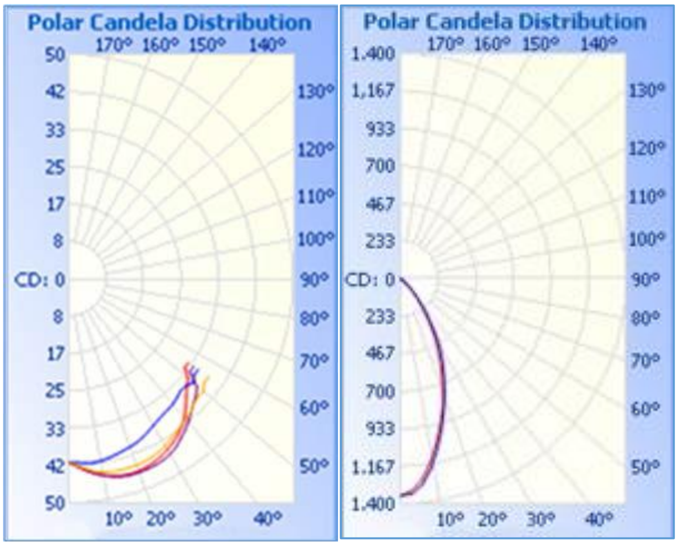

Figure 2. Luminous intensity distribution curves of L1 and L2.

2.2 Goal and Scope

The goal of this study is to assess and compare a new LED eco-lighting product with an existing LED lighting product to investigate their environmental impact and to find out how the impact is allocated in the luminaires' life cycle stages, and their components. Although both luminaires are table lamps that utilize LEDs as a light source, and have been designed for domestic indoor applications, they differ in several aspects: L1 produces ambient lighting, whilst L2 can be used to produce ambient, accent or task lighting. In addition, L2 produces higher light output (948 lm vs 102 lm) and illuminance (3825 lx vs 1312 lx) than L1. They also produce different luminous intensity distribution curves, and have different dimensions and weight. The results of this study will be used to inform decision-making related to product development activities, such as eco-benchmarking, eco-redesign of existing LED-based luminaires, and eco-design of new LED-based luminaires by considering the findings as a reference.

Functional unit

The function of a luminaire is to produce a specific quantity and quality of light for a period of time. The quantity of light is measured with the luminous flux (lm) of the luminaire, and the quality of light is mainly measured with the CCT (K) and CRI (although other quality-related parameters such as luminance/glare, flicker and ease of use can also be considered). The period of time is determined by the useful life of the luminaire. Although both, quantity and quality, affect the electricity consumption and environmental impact of the luminaire, the quantity of light is the main contributor to the electricity consumption of the luminaire. *Therefore, the functional unit used in this assessment is considered as the production of 948 lm of light (quantity of light) of 4000 K, and 65 of CRI (quality of light) during 40,000 h,* which is equivalent to the luminous flux (quantity) and CCT and CRI (quality) of the light produced by L2 (Table 1). This means that the quantity and quality of L1 has to be adjusted, (e.g. multiplied or divided by a factor), to equal the same light (quantity and quality) output as L2 to be compared. To equal the quantity of light, the amount of light produced by L1 (102.5 lm) has to be multiplied by 9.2 in order to produce the same light output as L2. Therefore, in theory, 6.4 lighting products of L1 would be needed to produce the same quantity of light produced by L2. The quality of light is the same in both luminaries, so there is no need to adjust it in this study; however, it could be adjusted by comparing the photopic curve with the light source specific spectral power distribution. Essentially, comparing the areas of both luminaires' light sources against the photopic curve will give you the differential in efficacy[23]. It is important to point out that, although it is known that LEDs with high CCTs (e.g. 6,500 K) are more (about 7%) energy-efficient than LEDs with low CCTs (e.g. 2,700 K)[24], and that LEDs with higher CRI (e.g. 90 vs 80) are about 16% less energy-efficient than LEDs with low CRI[23, 24], their differences in efficacy, and hence, power consumption are minor. This means that slight differences in quality of light (e.g. in CCT and CRI values) between luminaires have a minor influence in its electricity consumption. Despite this, the quality of light of both luminaire s have to be considered because this minor difference can become substantial when we scale the comparative results, (e.g. when it is compared the impact of hundreds of luminaires instead of one).

The period of time of the functional unit is determined by the useful life of the luminaire. LED-based luminaires' useful lives are usually determined by the LED and/or control gear's (e.g. driver) useful life. In this study, it has been considered as the LED useful life. The LED's useful life is provided by LED suppliers' lifespan datasheets, applying the TM-21-11 method[25]. However, this approach should be adopted with caution. This has been discussed in several studies[26,27] which state that LED lifespan datasheets cannot be used as a proxy to estimate the lifespan of a LED-based lighting system because when LEDs work as part of a lighting system in a real-life environment, their behavior may be different to the same LEDs tested outside lighting systems in controlled-lab environments. This has been confirmed in several studies, which show that LED-based luminaires may fail before their expected useful life[28,29]. This suggests the need to consider several possible useful life scenarios in LCAs, based on the assumption of a short (1,000 h), medium (15,000 h) or long (40,000 h) useful life, to account for early failure, random failure or change for upgrade, or long term failure due to natural wear out of components. These possible scenarios are examined in the 'Sensitivity analysis and scenarios' section below.

System boundaries

The boundaries of this LCA comprise cradle to grave life cycle processes. The product life cycle stages considered in this assessment include extraction and production of materials, manufacture, transport, use, and end of life of the luminaires. The packaging is not considered because both lighting products use the same packaging, so it does not affect the comparison results (Figure 3).

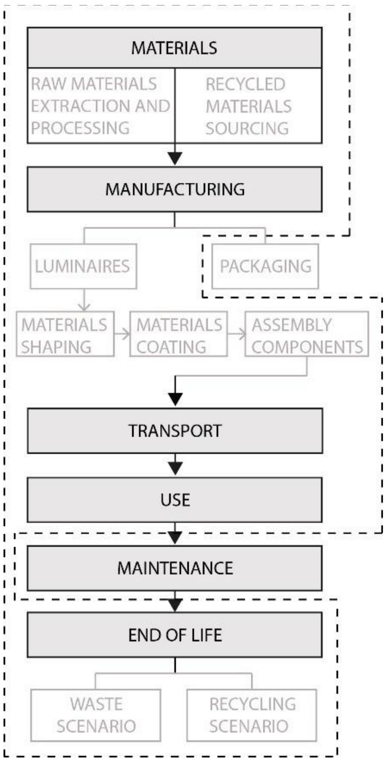

Figure 3. System boundaries.

To conduct the LCA, the following have been considered:

- Manufacturing:

The transport of the material from the extraction site to the material production factory, and from the material production factory to the product assembly factory has been taken into consideration in the assessment. The ‘Market datasets’ option from Ecoinvent 2016 database have been used when selecting materials and processes in the assessment, to account for market composition and transportation from material extraction to the assembly factory. The 100% recycled PET used in the assessment has considered the material loss of the recycling processes, as well as the energy used in the transport and processing of the re-used PET material.

- Use:

The maintenance during the ‘use’ stage of the luminaire has not been considered in the assessment. Maintenance may cause extra impact during the ‘use’ stage, but it can also extend the useful life of the luminaire and improve the luminaire efficacy, e.g. clean optical elements produce more light output. Although luminaire L2 can be dimmed, which, in theory, should reduce the electricity consumption, it has not been considered in the assessment because it is not known how much electricity can be saved by the integration of dimmers in LED luminaires.

- Transport:

This stage comprises the transport of the luminaire from the factory based in Spain to the final consumer in the Netherlands. For the transport of the luminaire from the factory in Spain to the retailer in the Netherlands, the total transport distance assumed is 2,063 km. This distance comprises two sub-distances: The transport from ONA factory to the Netherlands national point of the logistics company, 1,874 km, using 40 Ton lorries, and the transport from the Netherlands national point of the logistics company to the retailers, 189 km, using 3.5-7.5 Ton lorries.

- End of Life:

The end of life of the luminaires is difficult to predict, because this depends on consumer's personal disposal decisions. Nevertheless, two main possible end of life scenarios, domestic bin and recycling centre, are considered in this research. The 'domestic bin' scenario assumes that the product is disposed in a household bin and the household municipal waste process is followed. The 'recycling centre' scenario assumes that the luminaire is taken to a recycling centre where it is recycled. It is assumed that 80% of the luminaire is recycled and that 20% of the material is not recycled and is processed via the municipal waste scenario.

2.3 Life Cycle Inventory

The Bills of Materials (BoM) of each luminaire are shown in Appendices 1 and 2. The list of manufacturing processes to produce and shape the materials used to make each luminaire are shown in Appendices 3 and 4, and the list of transport and End of Life (EoL) processes used in both luminaires are shown in Appendix 5. The materials and processes data utilised in the assessment are selected from the recycled content model of Ecoinvent V.3.2 database[17].

2.4 Life Cycle Impact Assessment Method and Scenarios

Life Cycle Impact Assessment (LCIA) Method

The LCIA is the stage that follows the LCI. This phase of the LCA is aimed at assessing and interpreting the LCI (i.e. substances) collected in the previous phase. The LCIA usually consist of the following steps: 1) classification, 2) characterization, 3) normalization and 4) weighting of LCI substances. Simapro software allows selecting different LCIA methods, but this LCA has used ReCiPe V1.12[11] method. ReCiPe allows the provision of results in a broad set of midpoint and endpoint indicators, which can satisfy: 1) transparency of results, through 18 midpoint indicators, for users who want weighting-free results, and 2) weighted simplified results in more meaningful impact categories through three endpoint indicators. The Hierarchist (H) version was selected because it is the 'recommended' option of this method, which is based on the most common policy principles with regards to time-frame[11].

ReCiPe midpoint (H) shows the results based on eighteen midpoint impact categories: Climate change, Ozone depletion, Terrestrial Acidification, Freshwater Acidification, Marine Eutrophication, Human Toxicity, Photochemical Oxidant Formation, Particulate Matter Foundation, Terrestrial Ecotoxicity, Freshwater Ecotoxicity, Marine Ecotoxicity, Ionizing Radiation, Agricultural Land Occupation, Urban Land Occupation, Natural Land Transformation, Water depletion, Metal Depletion, and Fossil depletion. Recipe endpoint (H) shows the results on three endpoint impact categories: Human health, Ecosystems, and Resources Availability.

<u>Scenarios</u>

The assessment has been conducted based on six possible scenarios to check the sensitivity of the results. The most probable scenario has been considered as the base-case scenario, where the luminaire is used for 40,000 h, distributed in the Netherlands, and disposed in a domestic bin. The base-case scenario and other possible scenarios are shown in Table 2.

Scenarios	Country where is Manufactured	Country where is used	Useful life	Country where is distributed	Country where is disposed	Type of End of Life
S1	Spain	Netherlands	1,000 h	Netherlands	Netherlands	Domestic bin
S2	Spain	Netherlands	1,000 h	Netherlands	Netherlands	Recycling
S3	Spain	Netherlands	15,000 h	Netherlands	Netherlands	Domestic bin
S4	Spain	Netherlands	15,000 h	Netherlands	Netherlands	Recycling
S5 (base)	*Spain*	*Netherlands*	*40,000 h*	*Netherlands*	*Netherlands*	*Domestic bin*
S6	Spain	Netherlands	40,000 h	Netherlands	Netherlands	Recycling

Table 2. Scenarios description.

2.5 Interpretation of results of base-case scenario

This section shows the results based on the base-case scenario (Scenario 5). The results of the assessment of the two luminaires, L1 and L2, are presented in Figure 4 and Table 2.

Overall Results

Figures 4-6 and Table 3 show the environmental impact results (using midpoint and endpoint indicators) of the luminaires L1 and L2. In all midpoint impact categories, L2 has 60% or less environmental impact than L1 (Figure 4). The impact is even lower in the metal depletion impact category, where L2 has about 96% less impact than L1. This is because L1 uses a large amount of metals, (e.g. stainless steel and iron), for the frame compared with L2. L2 produces about 63% less CO_2 than L1, which is mainly due to the electricity consumed by the luminaire during the use stage. L2 produces less CO_2 than L1 because it has higher efficacy, e.g. L2 produces 55 lm/W while L1 produces 15 lm/W, indicating that L2 produces more light using less electricity. The results based on endpoint indicators (Figure 5) show that L1 has total higher (L1: 135 vs L2: 45 Pt) environmental impact than L2, and higher environmental impact in all the three impact categories (human health, resources and ecosystems).

It is estimated that approximately 84 Kg of CO_2 could be saved per luminaire per year if L2 model was used instead of L1. The results shown have not taken into account the use of the dimmer of L2, which, theoretically, would mean about 20% (estimated) energy savings, reducing the environmental impact of L2 further.

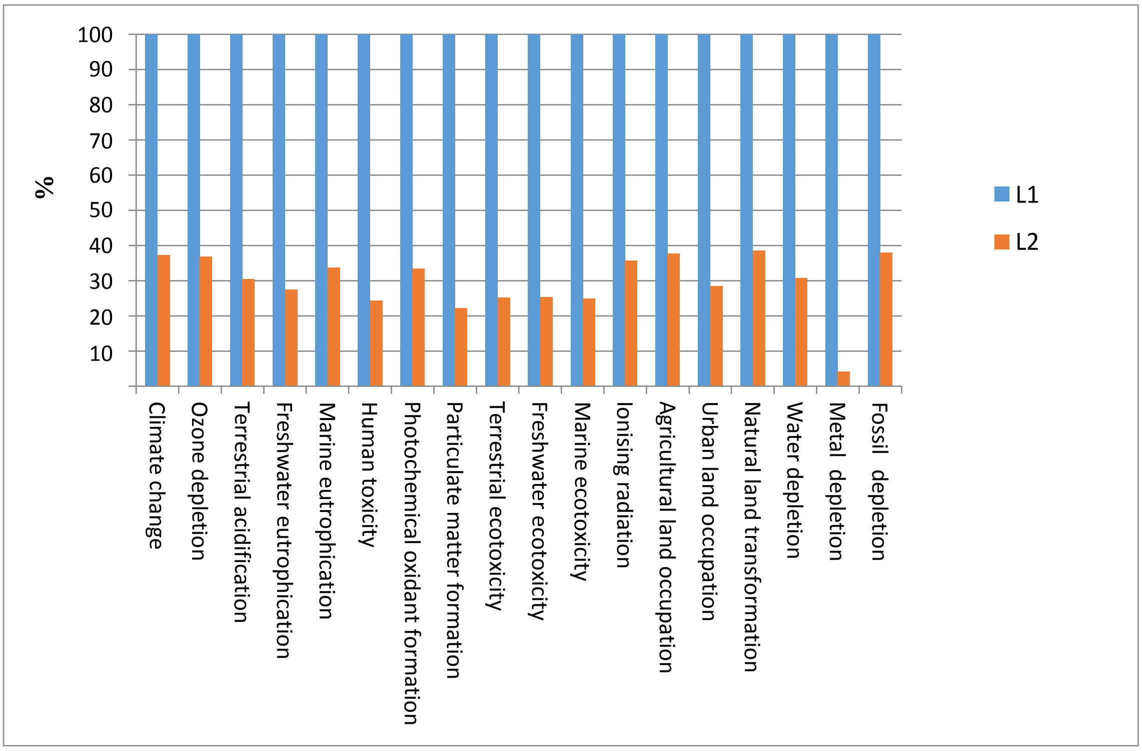

Figure 4. Environmental impact (midpoint indicators) per impact category of L1 and L2 in the base-case scenario.

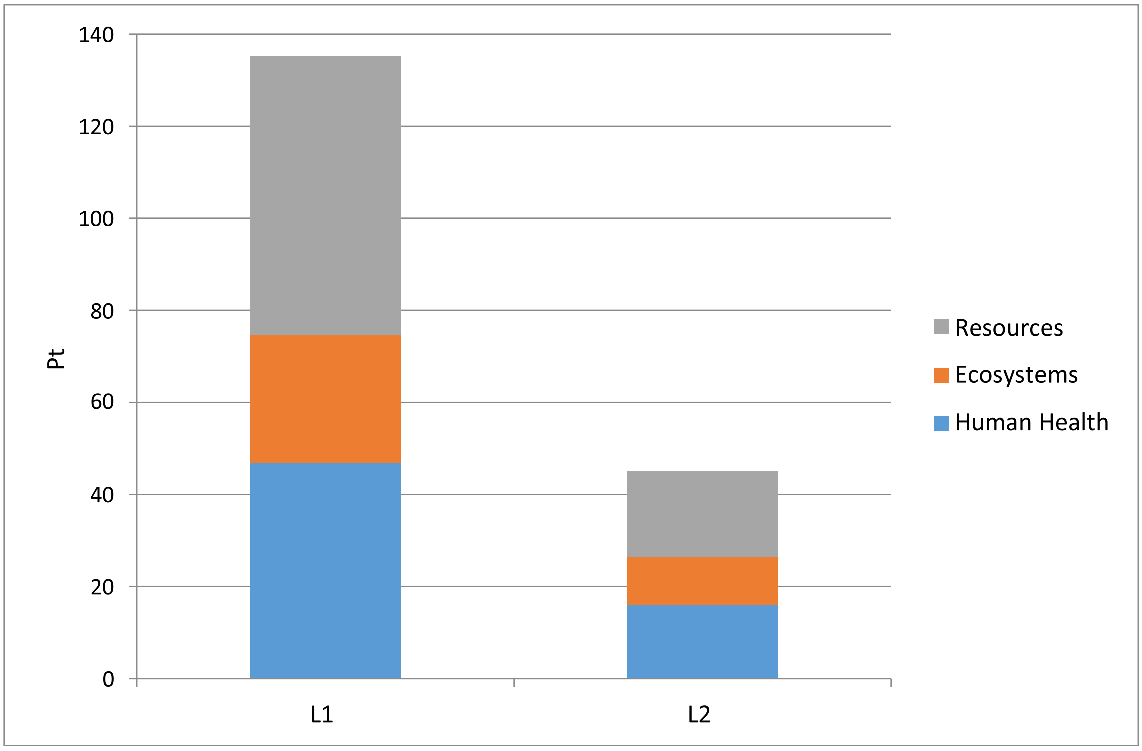

Figure 5. Environmental impact (endpoint indicators) per impact category of L1 and L2 in the base-case scenario.

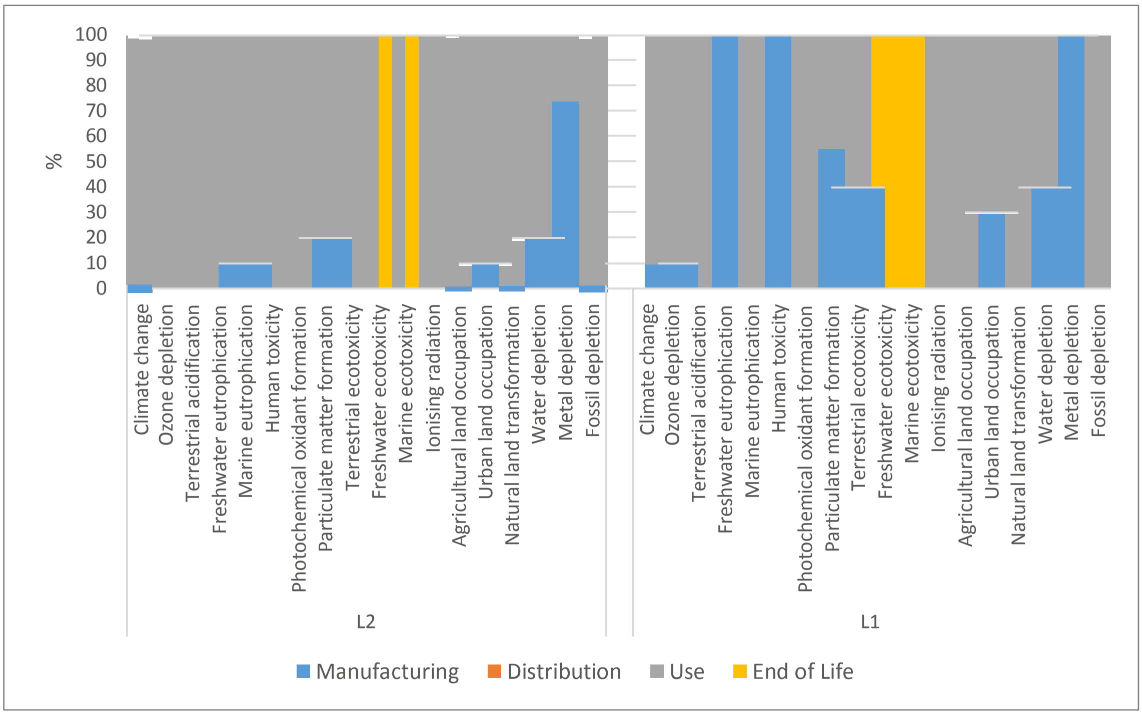

Figure 6. Environmental impact (midpoint indicators) of each life cycle stage of L1 and L2 in the base-case scenario.

Results of life cycle stages

Figure 6 and Table 3 also show the environmental impact per life cycle stages of both luminaires using midpoint indicators. The results reveal each stage's contribution to the total impact of the luminaires as follows:

- 'Use' is the life cycle stage with the highest impact in both luminaires. The impact of this life cycle stage is caused by the electricity consumed by the luminaires, which mainly affects the climate change, ozone depletion, natural land transformation, fossil depletion and ionizing radiation impact categories.

- ‘Manufacturing’ is the life cycle stage with the second highest impact in both luminaires on average (i.e. in almost all impact categories). The main impact categories that contribute to the impact produced in both luminaires in this life cycle stage are metal depletion and human toxicity. In L1, this life cycle stage produces about eight times more CO_2 and uses about thirty-one times more metal-based resources than in L2. This is due to the use of steel and iron in large amounts to manufacture the structure of L1.
- ‘End of life’ is the life cycle stage with the third highest impact in both luminaires, and represents an imperceptible impact in all the impact categories, except in freshwater ecotoxicity and marine ecotoxicity, which represent 57% and 54% of the total impact of those categories in the product life cycle in L1, and 37% and 36% in L2. The reduced impact at the end of life of L2 is due to the reduced amount of material disposed and processed in comparison with L1.
- ‘Transport’ is the life cycle stage with the lowest impact in both luminaires, and the impact is barely perceptible in the total impact. The impact categories that contribute more to the impact produced in this life cycle stage are Urban Land Occupation and Terrestrial Ecotoxicity, representing about 7% of the total impact of this category in the total product life cycle of L1, and about 2% in L2. L2 produces less impact in these categories due to its inferior weight compared with L1.

L1

Impact category	Unit	Total	Manufacturing	Transport	Use	End of Life
Climate change	kg CO2 eq	1.34E3	129	7.56	1.2E3	1.96
Ozone depletion	kg CFC-11 eq	6.6E-5	7.28E-6	1.38E-6	5.73E-5	7.94E-8
Terrestrial acidification	kg SO2 eq	2.15	0.739	0.0243	1.39	0.00109
Freshwater eutrophication	kg P eq	0.204	0.108	0.000696	0.0955	0.000106
Marine eutrophication	kg N eq	0.13	0.0328	0.00108	0.0956	0.000373
Human toxicity	kg 1,4-DB eq	262	171	2.08	87.5	1.49
Photochemical oxidant formation	kg NMVOC	2.34	0.523	0.031	1.78	0.00113
Particulate matter formation	kg PM10 eq	1.17	0.635	0.014	0.515	0.000572
Ionising radiation	kBq U235 eq	56.7	9.03	0.588	47	0.0595
Terrestrial ecotoxicity	kg 1,4-DB eq	0.0474	0.0193	0.00314	0.0249	8.33E-5
Freshwater ecotoxicity	kg 1,4-DB eq	40.4	9.91	0.0725	7.4	23.1
Marine ecotoxicity	kg 1,4-DB eq	36.8	9.96	0.0845	6.98	19.8
Agricultural land occupation	m2a	133	9.25	0.121	124	0.0167
Urban land occupation	m2a	7.98	2.39	0.569	5.01	0.00409
Natural land transformation	m2	0.268	0.0138	0.00298	0.251	-7.89E-6
Water depletion	m3	4.08	1.57	0.0273	2.48	0.00686
Metal depletion	kg Fe eq	289	280	0.302	7.99	0.0124
Fossil depletion	kg oil eq	440	32.4	2.75	405	0.0461

L2

Impact category	Unit	Total	Manufacturing	Transport	Use	End of Life
Climate change	kg CO2 eq	500	16.4	0.574	482	1.67
Ozone depletion	kg CFC-11 eq	2.43E-5	1.2E-6	1.05E-7	2.3E-5	1.75E-8
Terrestrial acidification	kg SO2 eq	0.657	0.0979	0.00184	0.557	0.000581
Freshwater eutrophication	kg P eq	0.0562	0.0178	5.29E-5	0.0383	6E-5
Marine eutrophication	kg N eq	0.0437	0.00471	8.22E-5	0.0383	0.000597
Human toxicity	kg 1,4-DB eq	63.8	27.9	0.158	35.1	0.657
Photochemical oxidant formation	kg NMVOC	0.781	0.0631	0.00235	0.715	0.0008
Particulate matter formation	kg PM10 eq	0.259	0.0508	0.0016	0.207	0.000267
Terrestrial ecotoxicity	kg 1,4-DB eq	0.0119	0.00158	0.000238	0.00999	0.000126
Freshwater ecotoxicity	kg 1,4-DB eq	10.2	3.5	0.00551	2.97	3.77
Marine ecotoxicity	kg 1,4-DB eq	9.16	3.09	0.00642	2.8	3.26
Ionising radiation	kBq U235 eq	20.3	1.35	0.0446	18.9	0.00595

Agricultural land occupation	m2a	50.3	0.715	0.00916	49.6	0.00233
Urban land occupation	m2a	2.27	0.213	0.0432	2.01	0.00214
Natural land transformation	m2	0.103	0.00233	0.000226	0.101	-1.01E-5
Water depletion	m3	1.26	0.26	0.00207	0.993	0.0024
Metal depletion	kg Fe eq	12.3	9.1	0.0229	3.21	0.00578
Fossil depletion	kg oil eq	167	4.64	0.209	163	0.0176

Table 3. Total and life cycle stage environmental impact (midpoint indicator) of L1 and L2 in the base-case scenario.

In the manufacturing stage of L2, the processes with the highest impacts are: 1) Production of Aluminum alloy (47%), 2) Production of recycled PET (12%), and 3) Injection molding process (5%). In the manufacturing stage of L1, the processes with the highest percentage of impacts are: 1) Production of steel (72%), 2) Production of iron (22%), and 3) Production of printed wiring board (6%).

2.6 Sensitivity analysis

The sensitivity of the results is analysed using six scenarios, shown in Table 2, to discover what would be the impact of the luminaires if they had different useful lives and end of lives.

The sensitivity analysis and scenarios are mainly focused on the use stage because it is the stage with the highest impact in both luminaires in the base-case scenario. One of the factors that affect the environmental impact in the use stage is the useful life of the luminaire. The useful life is affected by the manufacturing faults, operating conditions, and luminaire design[26]. A 'lumen depreciation long-term performance study' carried out by US DOE[28] showed that 5 out of 26 LED-based luminaires failed to produce their intended light output, which is below 70% of its light output, also called L70, within the first 1,000 h. This indicates that LED luminaires do not always have the useful life estimated by the LED suppliers, but rather follow the typical 'bathtub' curve (Figure 7) of electronic products[30], which shows three main periods: 'Early failure period', 'spontaneous failure period' and 'wear out period'.

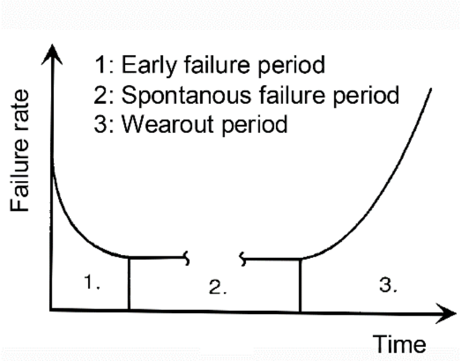

Figure 7. Bathtub curve: failure rate over time.

To consider the three typical periods observed in electronic products, three useful life scenarios were assumed: 1,000 h, 15,000 h, and 40,000 h. The scenario of 1,000 h assumed an early failure due to manufacturing faults, the scenario of 15,000 h assumed a random failure or the substitution of the luminaire due to technology/aesthetics upgrade, and the scenario of 40,000 h assumed an 'ideal' useful life, based on the average useful life of LEDs provided by LED suppliers. It is an 'ideal' scenario because this figure is provided by the LED supplier based on long-term extrapolations of shorter temporal tests conducted in lab ideal controlled operating conditions[26].

The scenarios also assumed the possibility that the luminaires could be disposed in the domestic bin or in the recycling centre.

Figures 8 and 9 show and compare the total environmental impact of L1 and L2 assuming six scenarios, (i.e. the base-case scenario and five additional scenarios).

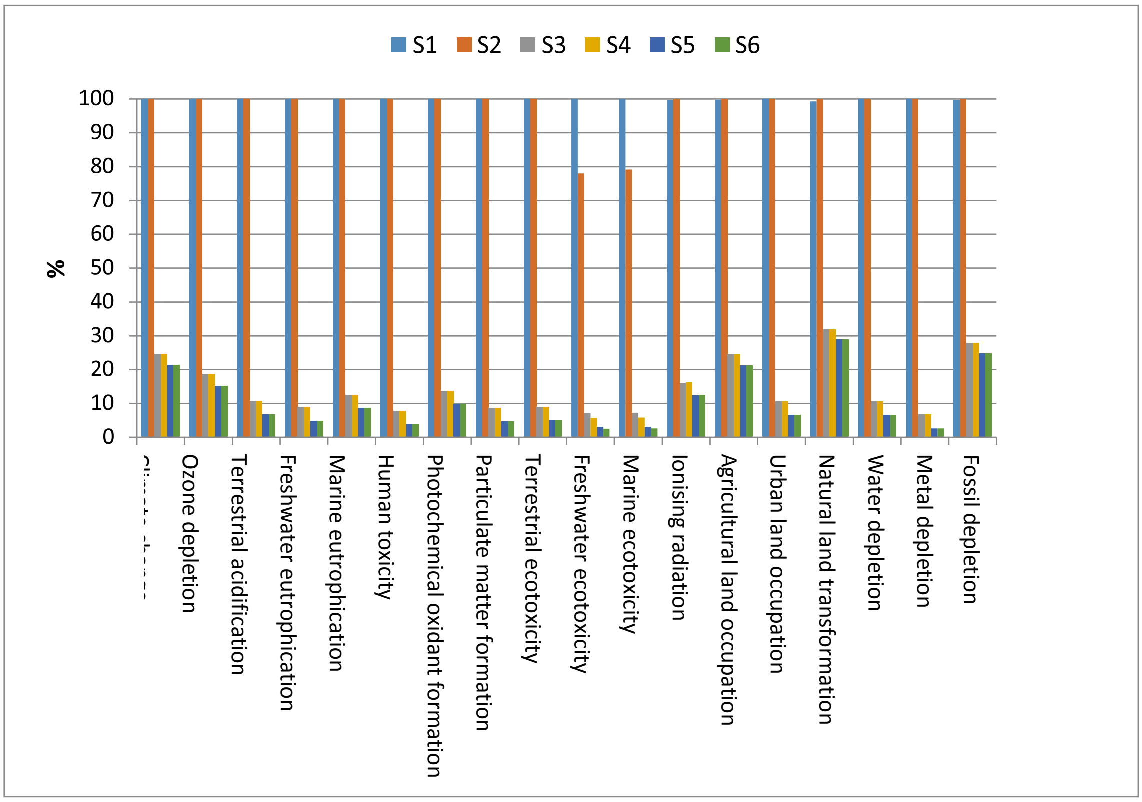

Figure 8.Total environmental impact (midpoint indicators) of L1 in scenarios 1-6.

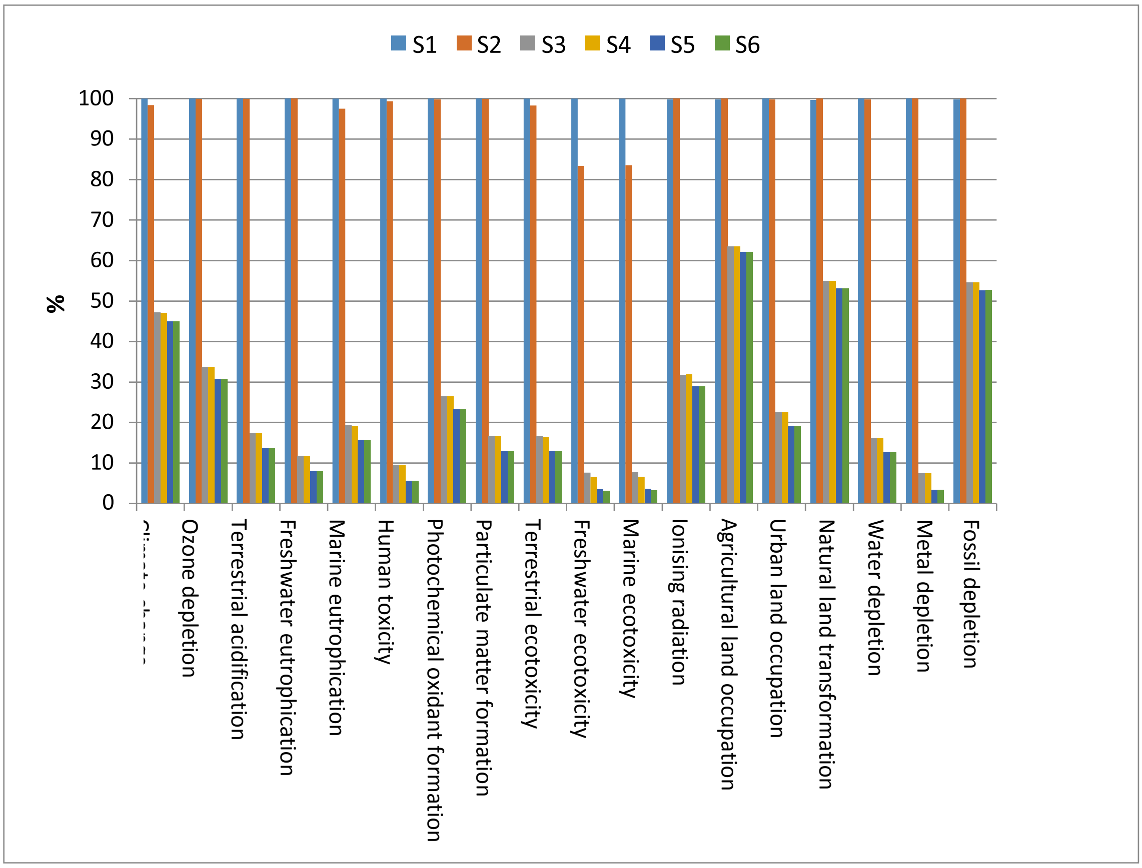

Figure 9. Total environmental impact (midpoint indicators) of L2 in scenarios 1-6.

In all the six scenarios, L1 has a higher environmental impact than L2. The life cycle stage with the highest impact in all scenarios is the use stage, except scenarios S1 and S2. In these scenarios the luminaires are assumed to have the shortest useful life, (e.g. 1,000 h.), where the manufacturing stage had the highest impact, followed by the use stage.

Scenario 1 (S1: 1,000 h – domestic bin) has the highest environmental impact, followed by scenario 2 (S2: 1,000 h – recycling). S2 has a slightly lower impact than S1 because the luminaire is recycled at the end of life. The reason for the minimal difference in impact is because the end of life stage plays a minor role in the total impact of the luminaires. S1 and S2 have the highest impact because the luminaires have the shortest useful life (1,000 h), which means that 40 luminaires have to be manufactured to provide the same functional unit (i.e. 40,000 h.). That is why the impact in all categories of S1 and S2 is produced mainly in the manufacturing stage.

Scenario 6 (S6: 40,000 h – domestic bin) has the lowest environmental impact, followed by Scenario 5 (S5: 40,000 h – recycling centre). S5 has a slightly higher impact than S6 because the luminaire of S5 is not recycled, e.g. domestic bin scenario, at the end of life. S5 and S6 have the lowest impact amongst all the scenarios because the luminaires of S5 and S6 have the longest useful life (40,000 h). The main impact in all categories occurs mainly during the use stage, followed by the manufacturing stage.

L1 produces 80% more CO_2 in S1 than in the base-case scenario S5 and L2 produces 60% more CO_2 in S1 than the base-case scenario S5. The difference in impacts between these scenarios is higher in L1, because L1 is less energy-efficient and uses more resources in manufacture.

3. Eco-design recommendations

The LCA results can be used to inform eco-designers' decision-making with the following purposes: 1) To eco-benchmark other LED luminaires manufactured, 2) To eco-redesign the luminaires assessed, 3) To have a general reference about typical life cycle stages and components with the highest impact in LED luminaires, and 4) To understand how different possible scenarios could affect the total impact, and the impact of each life cycle stage.

3.1 Implementation of Eco-design strategies

The comparative LCA results reveal that L2 has about 70% less impact than L1, so the eco-design features of L2 should be applied in the design of LED luminaires as far as possible; the life cycle stages with the highest impact in both luminaires are the use and manufacturing stages, which should be given priority when applying eco-design strategies.

The main eco-design strategies that can be implemented to reduce the impact in the life cycle stages of LED luminaires are:

In the use stage: a) Increase the luminous efficacy of the luminaire, b) Integrate dimmers, and c) Integrate smart controls, such as occupancy sensors, to reduce the energy used during the use stage.

In the manufacturing stage: a) Reduce the amount of virgin materials used, especially critical materials, or use recycled materials as much as possible, and b) Avoid or reduce the amount of manufacturing processes producing a negative impact on the environment and consuming resources/energy.

The end of life and, especially, the transport stages produce a minimal environmental impact, so the eco-design activities should firstly be focused on the use and manufacturing stages, and then consider the end of life and transport stages.

In the scenario where the product has a short useful life (e.g. 1,000 h.), manufacturing is the life cycle stage with the highest impact, rather than the use stage. This scenario may happen in LED luminaires with production faults or those utilised in extreme operating conditions. In this case, eco-design strategies have to be focused on the manufacturing stage first, followed by the use stage.

3.2 Challenges in the application of LCA for Eco-design

It is important to point out that when using the LCA method to assess and compare the environmental impact of LED luminaires, it is difficult to consider some features, such as those which contribute to reducing the environmental impact of the luminaire in the assessment. Features such as durability, light control, easy disassembly, and recyclability differ between luminaires and it should be possible to consider them in the LCA accurately and realistically without making assumptions, as these may affect the environmental impact results of each luminaire significantly. Usually, durable luminaires, which provide total light control, are easy to dismantle (to facilitate repair, upgrade and recycling), and are fully recyclable, should have less environmental impact than luminaires that do not present these characteristics, and, yet, the consideration of these features in a LCA presents the following challenges:

Durability

The durability of a luminaire can be considered in a LCA by adopting a longer or shorter useful life of the luminaire in the assessment. However, if there is no factual data about the useful lifespan of the luminaires to be assessed, given by the suppliers, making assumptions about the useful lifespan of each luminaire may result in invalid or misleading results.

Light control

Light direction and quantity control allow the saving of electricity, and hence diminish environmental impact, enabling the user to use the exact amount of light needed. Nevertheless, this feature cannot be considered, unless we know how much energy can be saved when using luminaires that allow light control. If there is no factual data based on a field study, which provides an average percentage of the electricity savings of luminaires that have specific light controls, then different assumptions have to be made for each luminaire, which may affect the validity of the results.

Easy disassembly

Easy disassembly can facilitate repair, upgrade and maintenance of the luminaire, thus extending its useful life. However it is difficult to quantify how much the useful life is extended in lighting products with these features. It is necessary to understand how different disassembly features affect the useful lifespan of lighting products, so a realistic useful life can be input in the LCA assessment.

Recyclability

The potential of a luminaire to be recycled cannot be fully considered in the LCA. It is difficult to consider in the LCA what percentage of the luminaire will be recycled, when considering a recycling scenario. The recyclability of a luminaire depends on many issues such as percentage of recyclable materials used, type and weight of each material, ease of disassembly and size of the luminaire, as well as the type of recycling facilities used to recycle the product. Therefore, when it is considered that the luminaire is going to be recycled it is not easy to estimate what percentage of material will be recycled from each luminaire.

To provide valid, accurate and realistic LCA comparative results between LED luminaires, it is necessary to have access to factual data, such as the useful life of the luminaires, how much energy is saved when using light controls, how long the useful life of the luminaires, that are easy to dismantle, can be extended, and hence repair, upgrade or recycle, and what is the recycling potential of a LED luminaire based on its architecture and composition for different recycling systems. All these features significantly affect the useful life, which is directly related with the use stage (i.e. the life cycle stage with the highest impact), so the study of how these features may affect the LCA is important for the comparative LCA of LED luminaires. Some of these features also affect the assessment at the end of life stage, because luminaires that are easy to dismantle and are highly recyclable, should have lower impact at the end of life stage, although this life cycle stage has less relative impact in the total impact of LED luminaires.

4. Conclusions

The comparative LCA results showed that, overall, L2 had about 60% or less impact than L1 in all midpoint impact categories in all scenarios, mainly due to the higher luminous efficacy of L2. It is estimated that approximately 84 Kg of CO_2 could be saved per luminaire per year if L2 model was used instead of L1.

It can be concluded that, in general, the use stage followed by the manufacturing stage are the life cycle stages with the highest impact in LED luminaires. Therefore, the most effective eco-design strategies to reduce the environmental impact are those which decrease power consumption, such as, increasing the luminaire efficacy, integrating dimmers, reducing the amount of functioning time when luminaires are not used through smart lighting controls (e.g. occupancy and light sensors), and reducing the amount of virgin materials used, especially the critical ones. The transport and end of life stages have less impact and consequently have low priority for eco-design. They could be excluded from the system boundaries of the assessment if human-economic resources are limited or for fast environmental impact assessments.

The definition of the functional unit is critical in the comparative LCA of LED lighting products. Unlike previous LCA-based studies of lighting products, the functional unit defined in this study is more comprehensive and suitable for the comparative LCA of LED luminaires. This research provides novel insights about how to select a suitable functional unit and suitable scenarios for the comparative LCA of LED lighting products, as well as eco-design recommendations, which are valuable contribution to knowledge in eco-design of LED luminaires.

This comparative LCA study uses the ReCiPe – Midpoint and Endpoint method that has not been used in previous LCA of LED luminaires, and provides a suitable updated replacement of eco-indicator method usually used by eco-designers of lighting products. ReCiPe can provide the results of the assessment in midpoint (i.e. weighting-free) and endpoint environmental indicators, which can satisfy different types of users' needs.

In this study, some features of the LED-based luminaires features have not been considered in the assessment, such as maintenance (e.g. repair and upgrade), durability, disassembly, and light control (e.g. dimmability and light direction), which affects the environmental impact of LED luminaries. Future studies could investigate how these features could be considered, aiming to improve the accuracy and objectivity of the comparative environmental impact assessment of LED-based luminaires.

Acknowledgements

The authors would like to thank Ona Product S.L. (www.ona.es) for providing their lighting products, as well as other necessary product life cycle information for this study.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors received financial support from the European Commission research program: CIP-EACI-ECO-INNOVATION. Grant N°: ECO/11/304409.

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Appendices

Abbreviations used in the appendices:

GLO: Data obtained from global processes**; RER:** Data obtained from European processes**; U:** Unit process; **S:** System process; **Alloc Rec:** Allocation Recycled content; **PET**: Polyethylene terephthalate; **PMMA**: Poly(methyl methacrylate); **ABS**: Acrylonitrile butadiene styrene; **PVC**: Polyvinyl chloride; **PC**: Polycarbonate.

Appendix 1: L1 BoM

Part	Component	Material	Ecoinvent Material	Weight (g)
Main-frame		Stainless steel	Steel, chromium steel 18/8, hot rolled {RER}| production | Alloc Rec, U	2836
Shade-frame		Iron	Pig iron {GLO}| market for | Alloc Rec, U	344
Shade		Parchment	Paper, wood containing, lightweight coated {RER}| market for | Alloc Rec, U	104
Cable (3.2 m)	Jacket	PVC	Polyvinylchloride, suspension polymerized {GLO}| market for | Alloc Rec, U	52
	Wire	Copper	Copper {GLO}| market for | Alloc Rec, U	42
Plug	Housing	ABS	Acrylonitrile-butadiene-styrene copolymer {GLO}| market for | Alloc Rec, U	7
	Internal switch comp.	Copper	Copper {GLO}| market for | Alloc Rec, U	2
Lamp frame		ABS	Acrylonitrile-butadiene-styrene copolymer {GLO}| market for | Alloc Rec, US	25
		Iron	Cast iron {GLO}| market for | Alloc Rec, U	3
Base		Iron	Pig iron {GLO}| market for | Alloc Rec, U	872
Switch	Housing	ABS	Acrylonitrile-butadiene-styrene copolymer {GLO}| market for | Alloc Rec, U	7
	Metal components	Copper	Copper concentrate {GLO}| market for | Alloc Rec, U	1

LED lamp	Metal thread	Iron	Cast iron {GLO}| market for | Alloc Rec, U	12
	Plastic internal structure	ABS	Acrylonitrile-butadiene-styrene copolymer {GLO}| market for | Alloc Rec, U	18
	Aluminum external case	Aluminum	Aluminum alloy, AlMg3 {GLO}| market for | Alloc Rec, U	10
	Heat sink plate	Aluminum	Aluminum alloy, AlMg3 {GLO}| market for | Alloc Rec, U	14
	Joint-ring	ABS	Acrylonitrile-butadiene-styrene copolymer {GLO}| market for | Alloc Rec, U	1
	Light diffuser	PET	Polyethylene terephthalate, granulate, bottle grade {GLO}| market for | Alloc Rec, U	11
	Printed Circuit Board (PCB)	N/A	Printed wiring board, surface mounted, unspecified, Pb free {GLO}| market for | Alloc Rec, U	5
	LED power supply	N/A	Transformer, low voltage use {GLO}| market for | Alloc Rec, U	3
	Capacitor	N/A	Capacitor, electrolyte type, < 2cm height {GLO}| market for | Alloc Rec, U	1
	Capacitor	N/A	Capacitor, electrolyte type, < 2cm height {GLO}| market for | Alloc Rec, U	1
	Capacitor	N/A	Capacitor, film type, for through-hole mounting {GLO}| market for | Alloc Rec, U	1
	Capacitor	N/A	Capacitor, tantalum-, for through-hole mounting {GLO}| market for | Alloc Rec, U	1
	Inductors	N/A	Inductor, ring core choke type {GLO}| market for | Alloc Rec, U	1
	Resistor	N/A	Resistor, metal film type, through-hole mounting {GLO}| market for | Alloc Rec, U	0.4
	LED metal support	Aluminum	Aluminum alloy, AlMg3 {GLO}| market for | Alloc Rec, U	14

Resistor	N/A	Resistor, metal film type, through-hole mounting {GLO}| market for | Alloc Rec, U	0.1
Resistor	N/A	Resistor, metal film type, through-hole mounting {GLO}| market for | Alloc Rec, U	0.1
Screws	Stainless Steel	Steel, chromium steel 18/8, hot rolled {GLO}| market for | Alloc Rec, U	1
LED	N/A	Light emitting diode {GLO}| market for | Alloc Rec, U	1

Appendix 2: L2 BoM

Part	Component	Material	Ecoinvent Material	Weight (g)
Housing - LED module		PET	Polyethylene terephthalate, granulate, amorphous {GLO}| market for | Alloc Rec, U - 100% Recycled	240
Lid - Housing LED module		PET	Polyethylene terephthalate, granulate, amorphous {GLO}| market for | Alloc Rec, U - 100% Recycled	60
Housing - driver module		PET	Polyethylene terephthalate, granulate, amorphous {GLO}| market for | Alloc Rec, U - 100% Recycled	272
Lid - housing driver module		PET	Polyethylene terephthalate, granulate, amorphous {GLO}| market for | Alloc Rec, U - 100% Recycled	82
Cable	Jacket	PVC	Polyvinylchloride, suspension polymerized {GLO}| market for | Alloc Rec, U	52
	Wire	Copper	Copper {GLO}| market for | Alloc Rec, U	42
Plug	Housing	ABS	Acrylonitrile-butadiene-styrene copolymer {GLO}| market for | Alloc Rec, U	8
	Internal switch comp.	Copper	Copper {GLO}| market for | Alloc Rec, U	2
Heat sink		Aluminum	Aluminum alloy, AlMg3 {GLO}| market for | Alloc Rec, U	126
Reflector		PMMA	Polymethyl methacrylate, sheet {GLO}| market for | Alloc Rec, U	54

Pole		Aluminum	Aluminum alloy, AlMg3 {GLO}| market for | Alloc Rec, U	236
Base		Aluminum	Aluminum alloy, AlMg3 {GLO}| market for | Alloc Rec, U	686
Joint-between-modules		PET	Polyethylene terephthalate, granulate, amorphous {GLO}| market for | Alloc Rec, U – 100% Recycled	18
LED		N/A	Light emitting diode {GLO}| market for | Alloc Rec, U	1
Driver	Housing	PC	Polycarbonate {GLO}| market for | Alloc Rec, U	36
	Printed Circuit Board (PCB)	N/A	Printed wiring board, through-hole mounted, unspecified, Pb free {GLO}| market for | Alloc Rec, U	10
	Capacitor	N/A	Capacitor, electrolyte type, < 2cm height {GLO}| market for | Alloc Rec, U	10
	Capacitor	N/A	Capacitor, electrolyte type, < 2cm height {GLO}| market for | Alloc Rec, U	0.1
	Capacitor	N/A	Capacitor, film type, for through-hole mounting {GLO}| market for | Alloc Rec, U	1
	Capacitor	N/A	Capacitor, film type, for through-hole mounting {GLO}| market for | Alloc Rec, U	1
	Capacitor	N/A	Capacitor, film type, for through-hole mounting {GLO}| market for | Alloc Rec, U	0.1
	Capacitor	N/A	Capacitor, auxiliaries and energy use {GLO}| market for | Alloc Rec, U	1
	Capacitor	N/A	Capacitor, auxiliaries and energy use {GLO}| market for | Alloc Rec, U	1
	Capacitor	N/A	Capacitor, auxiliaries and energy use {GLO}| market for | Alloc Rec, U	0.1
	Capacitor	N/A	Capacitor, auxiliaries and energy use {GLO}| market for | Alloc Rec, U	0.6

	Resistor	N/A	Resistor, metal film type, through-hole mounting {GLO}| market for | Alloc Rec, U	0.4
	Inductor	N/A	Inductor, auxiliaries and energy use {GLO}| market for | Alloc Rec, U	6
	Inductor	N/A	Inductor, ring core choke type {GLO}| market for | Alloc Rec, U	1
	Inductor	N/A	Inductor, ring core choke type {GLO}| market for | Alloc Rec, U	2
	Transformer 1	N/A	Transformer, low voltage use {GLO}| market for | Alloc Rec, U	36
	Transformer 2	N/A	Transformer, low voltage use {GLO}| market for | Alloc Rec, U	4
	Brackets	N/A	Aluminum alloy, AlMg3 {GLO}| market for | Alloc Rec, U	10
	Cable connectors	ABS	Acrylonitrile-butadiene-styrene copolymer {GLO}| market for | Alloc Rec, U	3
	Screws	Stainless steel	Steel, chromium steel 18/8, hot rolled {GLO}| market for | Alloc Rec, U	1
	Cables	PVC	Polyvinylchloride, suspension polymerized {GLO}| market for | Alloc Rec, U	0.3
		Copper	Copper {GLO}| market for | Alloc Rec, U	0.2
Circuit – platform		Aluminum	Aluminum alloy, AlMg3 {GLO}| market for | Alloc Rec, U	84
Reflector - ring		Aluminum	Aluminum alloy, AlMg3 {GLO}| market for | Alloc Rec, U	18
Circuit	Printed Circuit Board (PCB)	N/A	Printed wiring board, through-hole mounted, unspecified, Pb free {GLO}| market for | Alloc Rec, U	7
	LED power supply	N/A	Transformer, low voltage use {GLO}| market for | Alloc Rec, U	8
	Cable connectors	ABS	Acrylonitrile-butadiene-styrene copolymer {GLO}| market for | Alloc Rec, U	4

Resistor	N/A	Resistor, metal film type, through-hole mounting {GLO}| market for | Alloc Rec, U	0.4
Diode	N/A	Diode, glass-, for through-hole mounting {GLO}| market for | Alloc Rec, U	0.5
Integrated circuit	N/A	Integrated circuit, logic type {GLO}| market for | Alloc Rec, U	0.5
Resistor	N/A	Resistor, surface-mounted {GLO}| market for | Alloc Rec, U	0.4
Screws	Stainless steel	Steel, chromium steel 18/8, hot rolled {GLO}| market for | Alloc Rec, U	3

Appendix 3: List of manufacturing processes of L1

Part	Component	M. Process	Ecoinvent process	Amount	Unit
Main-frame		Laser machining	Laser machining, metal, with CO2-laser, 2000W power {RER}| laser machining, metal, with CO2-laser, 2000W power | Alloc Rec, U	1	min
		Drilling	Steel removed by drilling, conventional {RER}| steel drilling, conventional | Alloc Rec, U	10	g
Shade - frame		Welding	Welding, arc, steel {RER}| processing | Alloc Rec, U	20	mm
		Coating	Powder coat, steel {RER}| powder coating, steel | Alloc Rec, U	50	cm^2
Shade		N/A	N/A		
Cable	Jacket	Extrusion	Extrusion, plastic pipes {RER}| production | Alloc Rec, U	52	g
	Wire	Zinc plating	Zinc coat, pieces {RER}| zinc coating, pieces | Alloc Rec, U	25	cm^2
Plug	Housing	Injection molding	Injection molding {RER}| processing | Alloc Rec, U	7	g

	Metal component	Impact extrusion	Impact extrusion of steel, hot, 1 strokes {RER}| processing | Alloc Rec, U	2	g
Lamp frame		Injection molding	Injection molding {RER}| processing | Alloc Rec, U	25	g
		Impact extrusion	Impact extrusion of steel, cold, 2 strokes {RER}| processing | Alloc Rec, U	3	g
Base		Welding	Welding, arc, steel {RER}| processing | Alloc Rec, U	10	cm
Switc h	Housing	Injection molding	Injection molding {RER}| processing | Alloc Rec, U	7	g
	Metal component	Impact extrusion	Impact extrusion of steel, cold, 2 strokes {RER}| processing | Alloc Rec, U	1	g
LED lamp	Metal thread	Impact extrusion	Impact extrusion of steel, cold, 3 strokes {RER}| processing | Alloc Rec, U	12	g
	Plastic internal structure	Injection molding	Injection molding {RER}| processing | Alloc Rec, U	18	g
	Aluminum external case	Impact extrusion	Impact extrusion of aluminum, deformation stroke {RER}| processing | Alloc Rec, U	1	g
	Heat sink plate	Impact extrusion	Impact extrusion of aluminum, 3 strokes {RER}| processing | Alloc Rec, U	14	g
	Joint-ring	Injection molding	Injection molding {RER}| processing | Alloc Rec, U	1	g
	Light diffuser	Blow molding	Blow molding {RER}| production | Alloc Rec, U	11	g
	Printed Circuit Board (PCB)	N/A	N/A	5	g
	LED metal support	N/A	N/A	14	g

LED power supply	N/A	N/A	3	g
Capacitors	N/A	N/A	3	g
Inductors	N/A	N/A	1	g
Resistors	N/A	N/A	1	g
Screws	Coating	Zinc coat, pieces {RER}| zinc coating, pieces | Alloc Rec, U	1	cm^2
	Impact extrusion	Impact extrusion of steel, cold, 2 strokes {RER}| processing | Alloc Rec, U	1	g
	Wire drawing	Wire drawing, steel {RER}| processing | Alloc Rec, U	0.2	g

Appendix 4: List of manufacturing processes of L2

Part	Component	M. process	Ecoinvent process	Amount	Unit
Housing - LED module		Injection molding	Injection molding {RER}| processing | Alloc Rec, U	240	g
Lid - Housing LED module		Injection molding	Injection molding {RER}| processing | Alloc Rec, U	60	g
Housing - driver module		Injection molding	Injection molding {RER}| processing | Alloc Rec, U	272	g
Lid – Housing driver module		Injection molding	Injection molding {RER}| processing | Alloc Rec, U	82	g
Cable	Jacket	Extrusion	Extrusion, plastic pipes {RER}| production | Alloc Rec, U	52	g
	Wire	Zinc coating	Zinc coat, pieces {RER}| zinc coating, pieces | Alloc Rec, U	25	cm^2

Plug	Housing	Injection molding	Injection molding {RER}| processing | Alloc Rec, U	7	g
	Internal switch comp.	Impact extrusion	Impact extrusion of steel, hot, 1 strokes {RER}| processing | Alloc Rec, U	2	g
Heat sink		Milling	Aluminum removed by milling, small parts {RER}| aluminum milling, small parts | Alloc Rec, U	10	g
Reflecto r		Injection molding	Injection molding {RER}| processing | Alloc Rec, U	54	g
Pole		Extrusion	Impact extrusion of aluminum, deformation stroke {RER}| processing | Alloc Rec, U	236	g
Base		Sheet rolling	Sheet rolling, aluminum {RER}| processing | Alloc Rec, U	686	g
Joint-between-modules		Injection molding	Injection molding {RER}| processing | Alloc Rec, U	18	g
LED		N/A	Light Emitting diode, LED, at plant/GLO S	1	g
Driver	Housing	Injection molding	Injection molding {RER}| processing | Alloc Rec, U	36	g
	Printed Circuit Board (PCB)	N/A	N/A	10	g
	Capacitors	N/A	N/A	16	g
	Resistors	N/A	N/A	1	g
	Inductors	N/A	N/A	11	g
	Transformer	N/A	N/A	40	g
	Brackets	N/A	N/A	11	g
	Cable connectors	Injection molding	Injection molding {RER}| processing | Alloc Rec, U	3	g

	Screws	Coating	Zinc coat, pieces {RER}| zinc coating, pieces | Alloc Rec, U	0.6	g
		Impact extrusion	Impact extrusion of steel, cold, 2 strokes {RER}| processing | Alloc Rec, U	0.7	g
		Wire drawing	Wire drawing, steel {RER}| processing | Alloc Rec, U	0.1	g
	Cables	Extrusion	Extrusion, plastic pipes {RER}| production | Alloc Rec, U	0.3	g
		Zinc plating	Zinc coat, pieces {RER}| zinc coating, pieces | Alloc Rec, U	0.1	g
Circuit platform		Sheet rolling	Sheet rolling, aluminum {RER}| processing | Alloc Rec, U	84	g
Reflector ring		Milling	Aluminum removed by milling, small parts {RER}| aluminum milling, small parts | Alloc Rec, U	2	g
Circuit	Printed Circuit Board (PCB)	N/A	N/A	7	g
	LED power supply	N/A	N/A	8	g
	Cable connectors	Injection molding	Injection molding {RER}| processing | Alloc Rec, U	4	g
	Diode	N/A	N/A	1	g
	Integrated circuit	N/A	N/A	1	g
	Screws	Coating	Zinc coat, pieces {RER}| zinc coating, pieces | Alloc Rec, U	2	cm^2
		Impact extrusion	Impact extrusion of steel, cold, 2 strokes {RER}| processing | Alloc Rec, U	3	g

	Wire drawing	Wire drawing, steel {RER}| processing | Alloc Rec, U	0.4	g

Appendix 5: List of transport and End of Life processes used in L1 and L2

Stage	Process	Ecoinvent process	Amount	Unit
Transport	Truck - transport	Transport, freight, lorry > 32 metric tons, EUROS {RER}| transport, freight, lorry > 32 metric tons, EUROS | Alloc Rec, U	L1: 4390 L2: 2133	g g
	Lorry - transport	Transport, freight, lorry 3.5-7.5 metric ton, EUROS {RER}| transport, freight, lorry 3.5-7.5 metric ton, EUROS | Alloc Rec, U	L1: 4390 L2: 2133	g g
End of Life	Waste disposal scenario - Netherlands	Waste (Waste scenario) {NL}| treatment of waste | Alloc Rec.	L1: 4390 L2: 2133	g g