How to reduce the environmental impact of LED-based lighting products during the design process

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Copyright Statement

Abstract

Lighting products are essential in people's daily life. The global lighting market is expected to have over 100 billion euros' revenue by 2020 (McKinsey & Company 2012), and the introduction of Light Emitting Diode (LED) technology in the lighting sector is leading to a rapid growth of LED-based lighting products. By 2020, it is predicted that the LED-based lighting market share will be almost 70% of the total lighting market (McKinsey & Company 2012). However, lighting products also cause a negative impact on the environment during all the product life cycle stages, especially during the use stage. To date, there are no in-depth studies that have researched how to reduce the environmental impact caused by LED-based lighting products; therefore, research in this area is needed.

This research aims to contribute to the body of knowledge in this area by studying the following issues: 1) What the key product-related features are that influence the environmental impact of LED-based lighting products at each product life cycle stage, 2) What design recommendations can contribute to extend the lifespan of LED-based lighting products, 3) What the most effective and efficient method is to assess and compare the environmental impact of LED-based lighting products, and 4) What the most effective and efficient eco-design tools, techniques and methods are to reduce the environmental impact of LED-based lighting products during the design process, and how these can be integrated into an eco-design approach to reduce the environmental impact of LED-based lighting products.

The methodological approach followed to gather and analyse the data necessary to understand and answer the issues above mentioned has been based on the utilisation of two research methodologies: 1) Case study research, and 2) Survey. The case study research consisted of the study and critical examination of a real-world eco-design process of an awarded and patented LED-based product designed by the author in collaboration with several manufacturers. The data was collected using direct participatory observation. In addition to this, a survey was also conducted to understand the lifespan and causes of end of life of LED-based lighting products. The data was collected using on-line self-completion close-ended questionnaires.

This research contributes to body of knowledge of how to eco-design LED-based lighting products. In particular, it has made the following contributions to knowledge: 1) Identification of key product-related features that influence the environmental impact of LED-based lighting products at each product life cycle stage, 2) Definition of design recommendations to extend the lifespan of LED-based lighting products, 3) Development of a method to assess and compare the environmental impact of LED-based lighting products, and 4) Development of approach to eco-design of LED-based lighting products.

These contributions can be utilised to inform product developers' decision-making processes to reduce the environmental impact of this category of products.

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2. CASAMAYOR, J.L. and SU, D., 2011. Eco-design of lighting products: A study about integration of detailed/screening LCA software-based tools into design processes. In: MATSUMOTO, M.; YASUSHI, U.; MASUI, K. and FUKUSHIGE, S., ed., 2011. *Design for innovative value towards a sustainable society, Proceedings of Ecodesign 2011: 7th symposium on environmentally conscious design and inverse manufacturing Conference, Kyoto 30 November-2 December, 2011*. Berlin: Springer, pp. 608-613.
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ELPRO, Elektronik-Produkt Recycling GmbH (Germany)

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LEDinLight Ltd. (UK): This company ended its economic activities in 2013.

Nomenclature

AXX: Aaxsus AB

B2B: Business to Business

B2C: Business to Consumers

BoM: Bill of Materials

BS: British Standards

CAD: Computed Aided Design

CAM: Computer Aided Manufacturing

CBA: Cost-Benefit Analysis

CCT: Colour Correlated Temperature

CIE: International Commission on Illumination

CMS: Content Management System

CRI: Colour Render Index

DfC: Design for Compliance

DfD: Design for Disassembly

DFE: Design For Environment

DfR: Design for Recycling

EC: European Commission

EDM: Electrical Discharge Machining

EEE: Electrical and Electronic Equipment

EIA: Environmental Impact Assessment

ELCD: European LifeCycle Database

EMC: Electro Magnetic Compatibility

EMS: Environmental Management System

EN: English

EoL: End of Life

EPA: Environmental Protection Agency

EPAss: Environmental Product Assessment method

EPD: Environmental Product Declaration

EQ: Ecosystem Quality

ErP: Energy related Products

ERPA: Environmentally Responsible Product Assessment

ESD: Electro Static Discharge

EU: European Union

FMEA: Failure Mode and Effect Analysis

FR: France

H: Hour

HDI: High Intensity Discharge

HDPE: High Density Polyethylene

HH: Human Health

Hz: Hertz

ID: identification Device

IEC: International Electrotechnical Commission

IES: Illuminating Engineering Society

IOA: Input-Output analysis

IP: Ingress Protection

ISO: International Standardization Organization

ISTMT: In Situ Temperature Measurement Test

K: Kelvin

LAB: Laboratory

LCA: Life Cycle Assessment

LCC: Life Cycle Costing

LCI: Life Cycle Inventory

LCIA: Life Cycle Impact Assessment

LED: Light Emitting Diode

Lm: Lumen

LOR: Light Output Ratio

LP1: Lighting Product 1

LP2: Lighting Product 2

MECO: Materials, Energy, Chemicals, Other

MET: Material, Energy, Toxicity

MFA: Material Flow Analysis

N: Newton

NL: Netherlands

PBB: PolyBrominated Biphenyls

PBDE: PolyBrominated Diphenyl Ether

PCB: Printed Circuit Board

PDS: Product Design Specification

PET: PolyEthylene Terephthalate

PMMA: PolyMethyl MethAcrylate

Pt: Point

PVC: PolyVinyl Chloride

QFD: Quality Function Deployment

R&D: Research & Development

R: Resources

RoHS: Restriction of Hazardous Substances

SEA: Strategic Environmental Assessment

SEEA: System of Economic and Environmental Accounts

SELV: Safety Extra Low Voltage

SEO: Search Engine Optimization

TCA: Total Cost Assessment or Accounting

USP: Unique Selling Point

V: Volts

VAT: Value Added Tax

W: Watt

WEEE: Waste Electrical and Electronics Equipment

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Chapter 1: Introduction

This chapter introduces the research completed in this thesis. It begins by introducing the background of this research (1.1), followed by an explanation of why this research is needed (1.2), what the basic principles are and issues that determine the environmental impact produced by LED-based lighting products (1.3), and how this environmental impact can be reduced (1.4). In addition to this, it also explains the research motivation (1.5), the aim and objectives (1.6), the terminology used (1.7) and the structure of the thesis (1.8).

1.1 - Research background

This research has been supported by several research projects (Sustainable lighting product design, 2009; Ecolights, 2015; cycLED, 2015) funded by UK and the EU.
The outcome of the 'sustainable lighting product design' project was to produce the initial design (concept design) of the eco-lighting product developed and described in this thesis. The outcome of the 'Eco-lights' project was to further design, develop, manufacture and commercialize the eco-lighting product initially designed (concept design stage) in the 'sustainable product design' project. The outcome of 'cycLED' project was to reduce, re-use and recycle the critical materials contained in LED-based products. One of the outcomes of the project was to study the 'Lifespan study of LED-based lighting products', this study was coordinated and designed by the author, and several companies (from the project consortium) contributed to the distribution of the questionnaires and also provided feedback about the survey designed by the author.

Several companies (Ona Product S.L., Aaxsus AB, MASMedios S.L., Etap N.V., Riva GmbH, Braun Lighting GmbH, Philips Lighting B.V., ELPRO GmbH, and LEDinLight Ltd.) contributed to the research projects that supported this research. Ona Product S.L. was the manufacturer that co-developed (with the author), manufactured and commercialized the eco-lighting product, packaging and system that informed the case study. The lighting manufacturers: Etap N.V., Riva GmbH, Braun Lighting GmbH, Ona Product S.L. and LEDinLight Ltd. participated in the dissemination of the survey related to the Lifespan study of LED-based lighting products.

Fraunhofer IZM E.V., ELPRO GmbH., Eco-design Centre Wales, Sirris V.Z.W, and OUT E.V. provided feedback about the design of the survey (questionnaires) created by the author to investigate the lifespan of LED-based lighting products. ELPRO GmbH provided information about how LED-based lighting products are separated and recycled at the end of life. During the design of the eco-lighting product developed by Ona Product S.L., Aaxsus AB provided input about final consumers' preferences (Swedish market) and about how to improve the architecture of the eco-lighting product. Aaxsus AB and MASMedios S.L. also gave input in the design of the consumer survey within the case study, which was conducted during the design process in order to be aware of the consumer response to the first concepts/prototypes, as well as their preferences regarding lighting products in general.

1.2 - Why do we need Eco-lighting products?

People all over the world spend on average 12 hours per day without natural light. In addition, in some areas of the world (i.e. North of Sweden) people can spend 24 hours without natural light on specific dates (e.g. January). Natural light is not always available when we need it, and in some parts of the world, especially during specific seasons, it is much reduced even during day time. Nevertheless, people need light to continue with their daily lives, so the need for artificial light, and lighting products that can provide artificial light is a primary need for people. This may explain the high amount of lighting products sold each year. In 2010, the total market revenue of general lighting worldwide was around 52 billion euros, and by 2020, the world market is projected to reach 88 billion Euros (McKinsey and Company, 2012). However, all these lighting products, which are needed, purchased and used by people, also have a negative impact in the environment. Lighting products have an environmental impact during all the product life cycle stages, in particular, during its use stage. Lighting accounts for 19% of electricity consumption worldwide and 50% of electricity consumption of European cities (CELMA, 2011). In addition to the major impact caused during the use stage, they also have an environmental impact during extraction/refinement of materials, manufacturing, distribution and end of life. Lighting products may also contain toxic substances in its components or finishes, and these hazardous substances, even in small amounts, represent a high risk for the environment and human health.

1.3 - Environmental impact of lighting products

Lighting products have an environmental impact at each product life cycle stage. This environmental impact is caused by the consumption of materials and energy (input) and the production of waste and emissions (output). At each product life cycle stage, several processes occur, and each of these require input (materials and/or energy) and produce output (waste, emissions) (Fig. 1.1). In order to reduce the environmental impact of lighting products these inputs and outputs have to be reduced or eliminated.

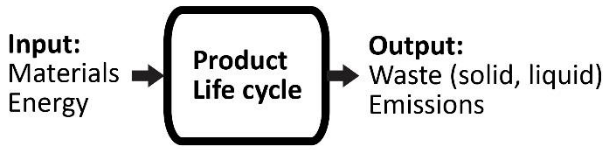


Figure 1.1. Causes of environmental impact

The product life cycle comprises several stages: Extraction and processing of materials; manufacturing (of product and packaging); distribution; use; and End of Life (EoL). In each stage, environmental impact is produced due to the use of materials and energy (input) and the production of waste and emissions (output) (Fig. 1.2).

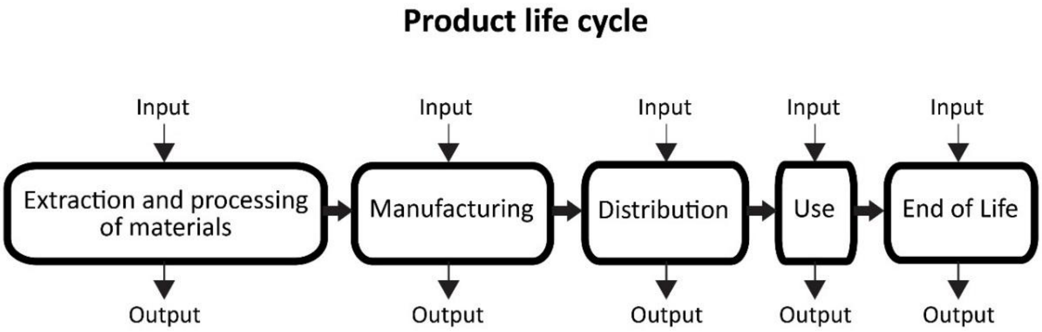


Figure 1.2. Product life cycle stages.

In order to reduce the environmental impact of lighting products, it has to be eliminated or reduced the amount of non-renewable material and energy used, and the production of emissions and waste at each lighting product life cycle stage.

1.4 - How to reduce the environmental impact of lighting products

The environmental impact of lighting products can be reduced or eliminated through different approaches which can be included within two general initiatives: Sustainable production and sustainable consumption. Sustainable consumption approaches can be difficult to implement successfully because consumers' behaviour is out of the manufacturers (and product developers) control. On the other hand, sustainable production approaches are easier to implement successfully, because the manufacturer (and product developer) usually has total control about how the lighting product will be designed, manufactured, packaged, distributed, commercialized and, to some extent, used and disposed.

Within the sustainable production initiative there are two approaches to decrease the environmental impact of lighting products: 1) to lessen the environmental impact of lighting products when these have already been designed and manufactured, also called 'end of pipe' solutions, 2) to diminish the environmental impact of lighting products at the design stage.

The reduction of environmental impact using the first approach is limited, because it is difficult to reduce the effect on the environment of a lighting product that has already been defined (i.e. there is no possibility to change the structure and materials used in the product), so the only possible strategies to lessen the impact when the product has been already designed and manufactured is to decrease-optimize the environmental impact of the industrial processes used during the product life cycle (i.e. manufacturing, distribution).

Using the second approach can produce higher environmental impact reductions, because it is at the design stage when the complete architecture and life cycle of the lighting product have to be decided (designed), and these design decisions will be reflected in the environmental impact of the lighting product. Once the lighting product has been defined, implementing strategies to reduce the environmental impact are usually costly and reduction effects on the environment are minimal. It has been stated that 80% of the product's total environmental impact is determined at the design stage (Charter and

Tischner, 2001; Mcalone and Bey, 2009), so special attention should be paid at the design stage of lighting products to reduce the negative impact of lighting products on the environment.

The reduction of the environmental impact of lighting product at the design stage can be implemented through three main types of design-based activities: 1) Eco-design and 2) Eco-redesign. A lighting product, service or system can be eco-designed from scratch, or eco-redesigned based on a reference lighting product/service/system. Eco-redesign only allows a limited amount of improvements (and hence environmental reductions) because the lighting product, service or system main structure cannot be modified, but usually requires less time and cost investment, which makes it a preferred activity when a company wishes to begin to reduce the environmental impact of its lighting products, services or systems.

This research focuses on the reduction of the environmental impact of LED-based lighting products from a sustainable production perspective, by adopting an eco-design approach.

1.5 - Research motivation

The introduction of Light Emitting Diode (LED) technology in the lighting sector is leading to a rapid growth of LED-based lighting products. By 2020, it is expected that the LED-based lighting market share will be almost 70% of the total lighting market (McKinsey & Company, 2012). Despite the growing demand of LED-based lighting products, there are not comprehensive studies about how to eco-design this type of product. Further understanding about how to eco-design LED-based lighting products is necessary to reduce their current and future impact on the environment.

The eco-design of LED-based lighting products requires knowledge about specific principles, tools and methods. In the available literature there are several methods and tools used by eco-designers, but these are focused on generic products (not in LED-based lighting products). Moreover, many of these recommend out of date tools and methods, and do not show a comprehensive approach of how to eco-design (assess and reduce) the environmental impact of LED-based lighting products.

1.6 - Aim and objectives of the research

The aim of this research is to increase the understanding about how to reduce the environmental impact of LED-based lighting products during the design process.

In order to achieve the aim, the research has studied the following questions:

- What are the *key product-related features that influence the environmental impact* of LED-based lighting products at each product life cycle stage?

- What *design recommendations* can contribute to extend the lifespan of LED-based lighting products? In order to answer this question, the lifespan and causes of end of life of LED-based lighting products had to be studied.

    a. Only the lifespan has been investigated with primary data collection and analysis, due to time limitations, and also because the lifespan is one of the product-related issues that is least understood as it is unknown why LED-based lighting products end their life and what can be done to avoid this.

    b. Other product-related issues (i.e. material quantity and type) and the strategies to avoid the impact they produce in LED-based lighting products have been investigated through literature review.

- What is the most effective and efficient *method to assess and compare* the environmental impact of LED-based lighting products?

- What are the most effective and efficient eco-design tools, techniques and methods to reduce the environmental impact of LED-based lighting products during the design process, and how these can be integrated into *an eco-design approach to reduce* the environmental impact of LED-based lighting products?

The key beneficiaries of the outcomes of this research are:

- LED-based lighting product developers, who have to design lighting products with low environmental impact.
- Policy makers, that need to inform regulations and directives in relation with the eco-design of (LED-based) lighting products.

1.7 - Terminology

The meaning of some of the most used terms that appear in the thesis are explained below:

- Eco-design, eco-redesign: At the design stage, there are several design-related activities (eco-design, eco-redesign) available to reduce the environmental impact of products, services and systems. Eco-design and eco-redesign both aim to reduce the environmental impact of products, services or systems, the key difference is that eco-design is applied to eco-design these from scratch, whilst eco-redesign is usually applied to eco-re-design an existing product, service or system to reduce its environmental impact.

- Eco-design, Design for the Environment (DfE) and sustainable design: Eco-design and Design for the Environment (DfE) are equivalent terms, both imply the design of products, services or systems taking into account their environmental impact. Eco-design is usually used in Europe and DfE in USA. In this thesis Eco-design has been used instead of DfE. Sustainable design is not an equivalent term, as it takes into consideration the environmental impact, as well as the social impact.

- Eco-lighting product: Eco-lighting product is used to define a lighting product with low environmental impact. The environmental impact of lighting products can be reduced with many eco-design strategies such as the use of less quantity and quality of materials, reduction of power consumption and easy disassembly. It should be highlighted that eco-lighting products only consider the environmental impact, the social impact is not considered. Sustainable lighting products consider the environmental and the social impact, but these are not the object of this research.

The term ‘eco-lighting product’ has been used consistently during the full thesis to convey a lighting product with low environmental impact.

- Design process: The term ‘design process’ used in this thesis includes the following design stages: concept design, embodiment design, detail design and testing/analysis.

- LED-based lighting product: This term is used to define a lighting product which uses LED as a light source.

1.8 - Structure of the thesis

This thesis is divided in eight chapters (Fig. 1.3): 1) Introduction, 2) Literature review, 3) Methodology, 4) Case study, 5) Method to assess and compare LED-based lighting products, 6) Lifespan of LED-based lighting products, 7) Approach to eco-design LED-based lighting products, 8) Conclusions and future research.

Chapter 1 introduces the background, the aim and the objectives of the research. Chapter 2 reviews: lighting products, services and systems types, eco-design methods and tools, and existing studies about the design and development of eco-lighting products, and environmental impact assessment of lighting products. Chapter 3 explains the methodology utilised in this research. Chapter 4 describes and examines the case study and the eco-design process followed. Chapter 5 explains the LCA-based method to assess and compare LED-based lighting products. Chapter 6 explains the study about the lifespan of LED-based lighting products. Chapter 7 shows the approach to eco-design LED-based eco-lighting products, and chapter 8 summarises the contributions to knowledge, and point out areas for further research.

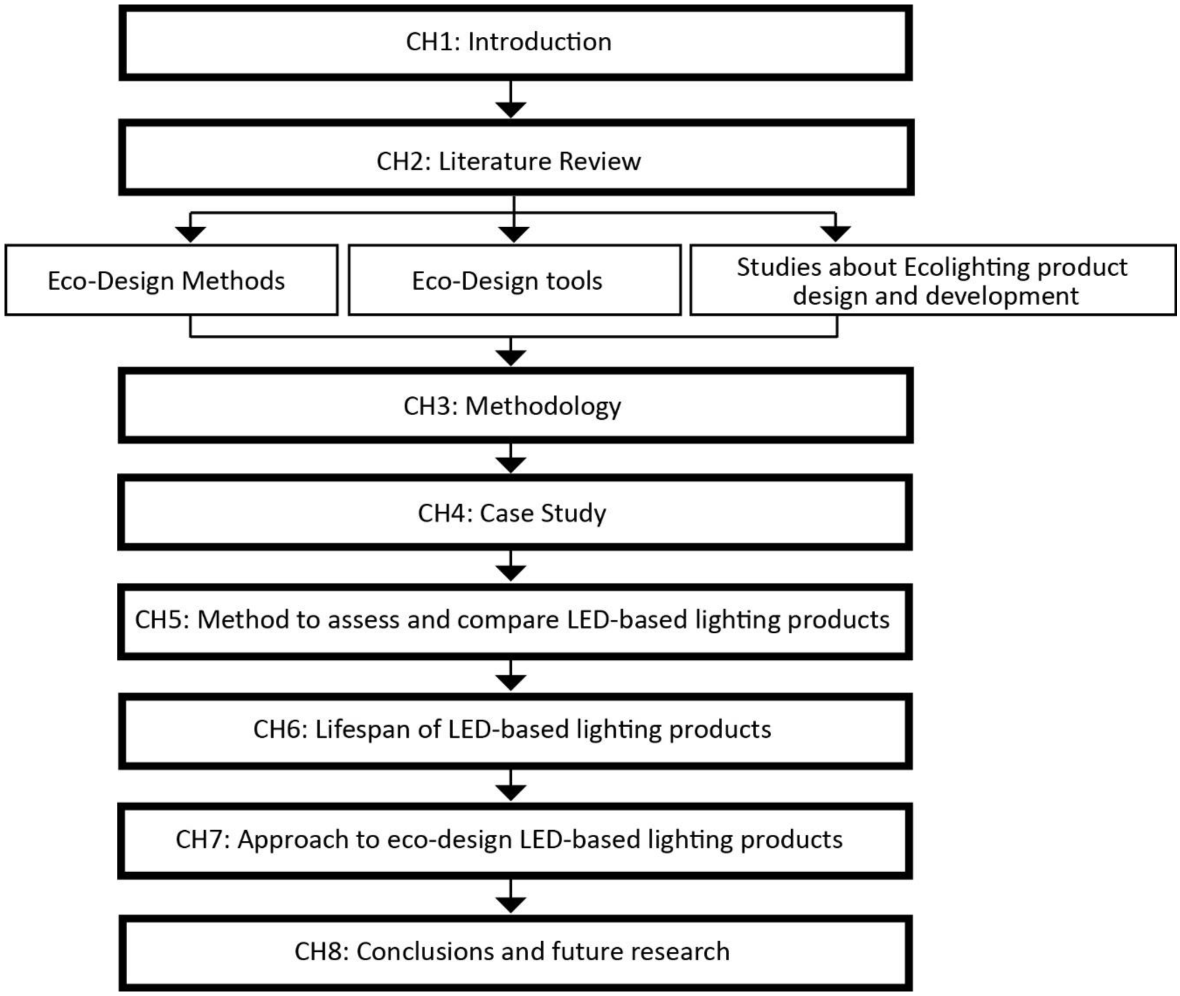


Figure 1.3. Thesis structure

Chapter 2: Literature review

This chapter reviews the lighting products, services and systems types (Section 2.1), the existing eco-design process models, methods and approaches to eco-design generic products and lighting products (Section 2.2) and the existing eco-design tools (Section 2.3). A summary of the review is provided in the last section (Section 2.4).

2.1 - Types of Lighting products, services and systems

Lighting products can function individually or within a system. In addition, light can also be produced as a service, that is, the consumer does not buy or own the lighting product, instead, they pay the service of 'renting' a specific quantity and quality of light for a period of time. The next sections (section 2.1.1, 2.2.1.1 and 2.2.1.2) review the main types of lighting products based on the kind of light produced (i.e. accent lighting) and the light source utilised (i.e. LED). Lighting systems and lighting services are also briefly reviewed (sections 2.1.2, 2.1.2.1, and 2.1.2.2) to contextualise LED-based lighting products within the wider field of lighting.

2.1.1 - Types of Lighting products

Lighting products can be classified based on different criteria. In this section they have been categorised based on two typical criteria used in the lighting sector: a) type of light produced and b) type of light source utilised.

2.1.1.1 - Types of Lighting products - Based on type of light produced

There are three main types of lighting products based on the type of light produced. Lighting products that produce: Accent lighting, ambient lighting, and task lighting (ALA, 2016).

- <u>Lighting products that provide *accent* lighting</u>: This type of lighting product provides accent lighting, which is usually used to create visual interest. To be effective, accent lighting requires at least three times as much light on the focal point as the general lighting around it.

- Lighting products that provide *ambient* lighting: This type of lighting product provides general lighting which radiates a comfortable level of brightness.

- Lighting products that provide *task* lighting: This type of lighting products provides task lighting usually utilised to perform specific tasks such as reading, sewing, cooking, homework, hobbies, crafts. Task lighting should be free of distracting glare and shadows but bright enough to prevent eyestrain.

All the types mentioned above can also be further classified in lighting products that provide direct or indirect light. For example, ambient lighting products usually provide indirect light and accent and task lighting products usually provide direct light.

In general, lighting products that provide task lighting are more energy-efficient than those that provide accent or ambient lighting, because the Light Output Ratio (LOR), which is defined by the amount of light that exits the lighting product divided by the amount of light produced by the light source, is higher. For example, ambient lighting products usually use a lamp shade which blocks the light produced by the light source, which means that most of the light produced is blocked and therefore not used, making the lighting product less energy-efficient.

There is no correlation between the type of light provided by lighting products and the type of light source utilised, which means that any type of light source can be used to produce any kind of light, although LEDs are directional light sources, and hence are more suitable to produce accent or task lighting.

2.1.1.2 - Types of Lighting products - Based on light source utilized

Lighting products can also be classified based on the light source utilised. The main light sources utilised in lighting products are: Incandescent, halogen, compact fluorescent, linear fluorescent, metal halide, high pressure sodium, low pressure sodium, and LED (Zumtobel, 2013).

The light source is one of the components that has more influence on the environmental impact and performance of lighting products, because they affect the energy consumed during the use stage, which is the product life cycle stage with the highest impact. The following issues of the light sources affect the environmental impact of the lighting product: useful life, luminous efficacy, resistance to shock, dimmability, directional light, hazardous substances content.

- Useful life: Longer lasting light sources cause less environmental impact because fewer replacements of new light sources are needed during the lighting product useful life. Table 2.1 (US DoE, 2009a) shows how LEDs have a significantly longer useful life compared with other light sources, that is why it is the best choice in order to reduce the environmental impact of the lighting product.

Light source	**Useful Life (hours)**
Incandescent	750-2,000
Halogen	3,000-4,000
Compact Fluorescent (CFL)	8,000-10,000
Metal halide	7,500-20,000
Linear Fluorescent	20,000-30,000
High-pressure sodium	10,000-40,000
Low-pressure sodium	18,000-20,000
LED	35,000-50,000

Table 2.1. Useful life of different types of light sources.

- Luminous efficacy: The luminous efficacy is obtained dividing the amount of lumens produced by the light source by the energy consumed (lm/W), higher values indicate that the light source produce more light output with less power consumption. The luminous efficacy of the lighting product is mainly influenced by the luminous efficacy of the light source utilised. Thus, although the efficiency of the driver and the optical system also influence the energy efficiency of the lighting product, their importance is secondary. That is why the use of light sources with the highest luminous efficacy is key in reducing the power consumption (energy used) during the use stage of the lighting product. Table 2.2 (US DoE, 2013) shows how LEDs are one of the light sources with the highest luminous efficacy, with values similar to low pressure sodium light sources. The luminous efficacy of LEDs has been improving since 2013 in comparison with other light sources, and the latest luminous efficacy of LEDs (e.g. Samsung S-series, Samsung, 2016) shows values up to 205 lm/W. These values are expected to improve further in the future.

Light source	**Luminous efficacy (lm/W)**
Incandescent	5-12
Halogen	4-25
Compact Fluorescent (CFL)	45-80
Metal halide	64-120
Linear Fluorescent	80-105
High-pressure sodium	64-150
Low-pressure sodium	100-200
LED	100-160

Table 2.2. Luminous efficacy of different types of light sources.

Although low pressure sodium light sources also have high luminous efficacy, these do not have the flexibility or reduced size to be included in domestic applications. On the other hand, LEDs, due to their small size and easy-to-retrofit technology can be used as a substitute of other less energy-efficient light sources such as incandescent, halogen and compact fluorescent used in domestic applications. Low and high pressure sodium technologies are used mainly in street lighting applications.

- Resistance to shock: Another feature of light sources that can affect their environmental impact is their resistance to shock. Often, lighting products stop working due to light source failure caused by shock. Shock can take place during transport, or when the lighting product is used in operating conditions with high-vibration. LEDs are highly resistant to shock, which means they are less prone to failure by impact, extending their useful lifespan, and the lifespan of the lighting product. Less light source failures mean fewer replacements with new light sources, thus reducing the environmental impact caused by new components, or a new lighting product, in cases where no one can diagnose the failure of the lighting product. The other light source technologies, are extremely fragile and prone to failure by shock.

- Dimmability: The possibility to dim the light output of the light source also affects the environmental impact of the lighting product. Light sources that are dimmable (continuously or step-by-step) can reduce their energy consumption, because when the light source is dimmed less luminous output is produced and therefore less energy consumed. Additionally, it can also increase the useful lifespan of the light source and the lighting product because when the lighting product is dimmed the lighting system is not used at full capacity, and the wear out process of electronic components is delayed. All the main light sources are dimmable, although some are easier to dim than others. LEDs are easily dimmable.

- Directional light: Light sources usually emit light in all directions. This means that to control the light direction, optical systems (e.g. reflectors, diffusors) have to be used. The use of optical systems increases the environmental impact of the product because more components are needed in the lighting product. LEDs are directional light sources, which usually produce light in one direction (beam). This means that, in some cases, additional optical systems may not be needed in the design of the lighting product.

- Hazardous substances content: Although all the light sources contain hazardous and scarce substances to some extent. Some of them contain high levels of harmful substances. For example, compact and linear fluorescent contain high percentages of mercury, a highly hazardous substance, which can be released if the light source breaks during the use stage, or when the product is disposed and/or recycled.

2.1.2 - Types of Lighting services and systems

In addition to the typical case where the lighting product is purchased and used as an individual unit for a specific lighting purpose/application, lighting products can also be used within a system (lighting systems). Also, light can be purchased as a service. In this case, the consumer does not purchase and own a lighting product/s, instead, they buy the service where it is specified the provision of a specific quantity/quality of light for a period of time.

2.1.2.1 - Lighting services

Lighting-as-a-service allows the consumer to buy the service (e.g. light) instead of the product (e.g. lighting product) (Ellen Macarthur Foundation, 2016). This option presents several advantages for the lighting service provider (company), the consumer and the environment. First, the company providing the lighting service have full control of their lighting products and systems over their lifecycle, because they manufacture, maintain (including upgrade) and re-use/recycle the lighting product and system. This has benefits for the company because they can collect and re-use their products when they fail and provide additional services to customers, such as maintenance and upgrading to increase revenues.

The consumer also receives benefits because if the product fails, its performance decreases, and/or new upgrades appear in the market: the company will provide all these services. From an environmental point of view, there are significant benefits. Lighting products and systems have a longer life since they are maintained, repaired and upgraded if needed, resulting in the production of fewer lighting products and consequently a diminished environmental impact. Also, as they are well maintained they function more efficiently. Finally, the end of life of the lighting products is under control of the company, so the company can collect and re-use or re-manufacture the lighting products at the end of life, ensuring its proper re-use or recycling.

One of the problems of this option is that many consumers want to buy and own the lighting product instead of buying the lighting service. This option works better in non-domestic lighting applications (e.g. public buildings, companies).

2.1.2.2 - Lighting systems

Lighting products can also work as part of a system. In that case, lighting products are connected with sensors, and a 'control unit' via wire or wireless communications. The 'control unit' usually has some kind of 'intelligence' (usually in the form of algorithms) embedded, which can interpret the information captured by the sensors or other building systems (e.g. AC system) information/data to trigger some behaviour (e.g. dimming of lights) in the lighting units. The 'intelligence' of the system can vary in complexity depending on the application. This type of systems are usually called 'Smart lighting' (Philips, 2016), and have become mainstream in many non-domestic lighting applications (e.g. hospitals, universities). The implementation of lighting systems in domestic applications is less common because these systems can be costly and difficult to install. In addition, the deployment of these systems makes sense when the running cost savings outweigh the initial investment of material and installation. From an environmental point of view, these systems can save energy during the use stage, and also contribute in extending the lifespan of the lighting products by facilitating monitoring and maintenance.

2.2 - Eco-design process models

One of the approaches to reduce the environmental impact caused by lighting products is sustainable production, that is, the reduction of the environmental impact of lighting products during the development and manufacturing stages. In addition, one of the most effective manners to reduce the environmental impact of lighting products is during the design process, where 80% of the environmental impact of the product is decided (Charter and Tischner, 2001). For this reason, much attention has been paid to this topic in the past, and a substantial amount of knowledge has been produced in relation to: 1) the consideration of environmental aspects in products (Mcdonough and Braungart, 2002; Shedroff, 2009; Hinte, 2004; Wimmer et al., 2010; Walker, 2006; Papanek, 1998; Graedel and Allenby, 1996; Giudice et al., 2006; Billatos et al., 1997; Wenzel et al., 1997); 2) the consideration of the environmental impact of products during the design process (Fiksel, 2009; Bhamra and Lofthouse, 2007; Vezzoli and Manzini, 2008; Rodrigo and Castells, 2002; Niemann, 2009; Kärnä, 2002; Bergendahl, 1995; Tingstrom et al., 2006); and 3) about the development of eco-design methods through the integration of eco-design tools in traditional design processes (Tischner et al., 2000; Brezet and Van Hemel, 1997; Dewulf, 2003; Jansen and Stevels, 1998; Wimmer et al., 2004; ISO, 2002; UNEP and TU Delft, 2006; Lewis et al., 2001; Stevels, 2007; Mcaloone and Bey, 2009; Ulrich and Eppinger, 2008; Knight and Jenkins, 2009; Vinodh and Rathod, 2010; Platcheck et al., 2008).

Some of the studies that have been carried out (Hanssen, 1999; Byggeth, Broman and Robert, 2007; Waage, 2007; Charnley et al., 2011; Maxwell and Van der Vorst, 2003; Garetti et al., 2012; Maxwell et al., 2006; Ge and Wang, 2007) present general approaches or frameworks (not step-by-step methods) for companies explaining how to reduce the environmental impact of a product or service, or how to produce more sustainable products. Other studies have focused on specific stages or processes (not the complete design process) of the eco-design process only (Pigosso, C.A. et al., 2010; Gehin et al., 2008; Vinodh and Jayakrishna, 2011; Kengpol and Boonkanit, 2011; Van der Zwan and Bhamra, 2003), and only a few studies (Tischner et al., 2000; Wimmer et al., 2010; Dewulf, 2003; Mcaloone and Bey, 2009; Brezet and Van Hemel, 1997; Nielsen and Wenzel, 2002) provide a full step-by-step prescriptive design process model to reduce the environmental impact of generic products, although these methods have not been updated with the latest knowledge about eco-design tools, and focus on generic products only.

The majority of the models and methods have been developed to eco-design generic products, and only a few studies have been focused on providing eco-design guidelines to develop specific categories of products such as electric-electronic products (Rodrigo and Castells, 2002; Kärnä, 2002). However, there are no comprehensive and detailed studies focused on the design of eco-lighting products, and although there is a study (Schmalz and Boks, 2010) related to design of eco-lighting products, this is focused on how to reduce the environmental impact of lighting products by changing the user behaviour only, so it is not considered comprehensive enough.

One of the biggest problems of existing eco-design tools and methods utilised to eco-design generic products is that they are not applied by product developers and/or implemented successfully by companies. Consequently, other studies have looked at why these eco-design methods are not implemented (Deutz et al., 2013; Petala et al., 2010; Boks, 2006; Spangerberg et al., 2010) and how these could be improved to have a better acceptance by users (Tingstrom and Karlsson, 2006; Kaebernick and Sun, 2003; Byggeth and Hochschorner, 2006; Lofthouse, 2006; Lindahl, 2006; Lindahl, 2005; Le Pochat, Bertoluci and Froelich, 2007), and an improved integration in product development processes to ensure a wider implementation.

This section (Section 2.2: Eco-design process models) is divided in two additional sections: Section 2.2.1 (Eco-design models for generic products), and section 2.2.2 (Eco-design models for lighting products). Section 2.2.1 reviews the existing eco-design process models used to eco-design generic products (non-specific categories of products). Section 2.2.2 reviews the existing eco-design process models used to eco-design lighting products (Specific categories of products).

2.2.1 - Eco-design models for generic products

The eco-design process is similar to the traditional design process, the only difference is that in the eco-design process, environmental considerations are also taken into account during the design process. This means that product developers must also be able to assess the environmental impact of concepts/design features during the design process, in addition to other parameters. That is why an additional set of eco-design tools (not used in traditional design processes) that can assess, and help/guide to reduce the environmental impact of the product have to be included in the eco-design process.

From a sustainable production perspective, the most effective manner to reduce the environmental impact of a product is during the design stage. Once the product has been defined it is very difficult and inefficient to reduce the environmental impact of the product (Lewis et al, 2001). The difficulty in reducing the environmental impact of a product over the product life cycle is shown in Fig.2.1.

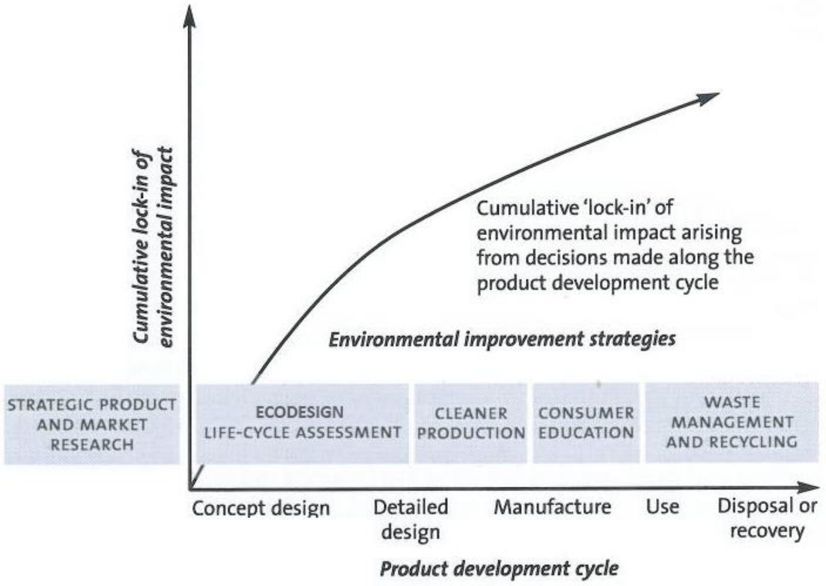


Figure 2.1. Conceptual representation of environmental impact over a product life cycle.

There are several design process models or methods to design generic (any category) products with low environmental impact. The more relevant approaches, design models and methods are described and analysed in this section.

Another key feature of eco-design processes or models is that the full life cycle of the product is considered in the design process, this is called 'life cycle design' (Vezzoli and

Manzini, 2008) and it consists of considering and designing the full product life cycle (all the product life cycle stages).

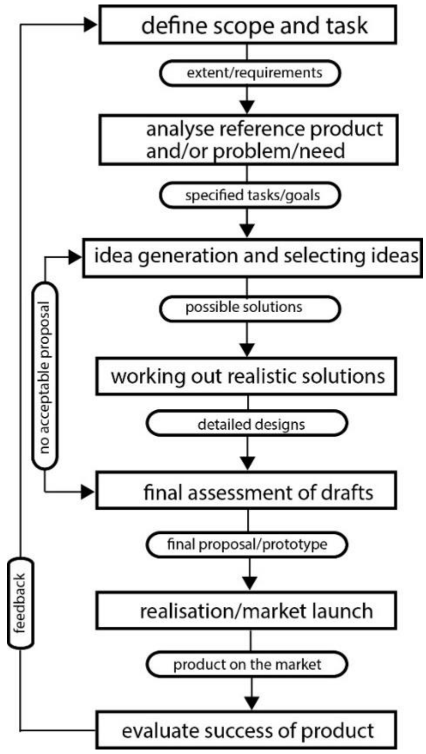


Figure 2.2. Tischner eco-design method.

The eco-design method developed by Tischner (Tischner et al. 2000), is comprehensive. It explains (and prescribes) the necessary tasks to be performed at each stage (Fig. 2.2) of the design process to design a product with low environmental impact.

One of the advantages of this method is it provides an actual step-by-step detailed process to product designers explaining what to do at each design process stage, and which tools can be used at each stage.

One of the disadvantages of the method is that it does not give much information about the embodiment and detail design stages of the design process. The method assumes that once the concept is selected this is further detailed (Fig. 2.2: ‘detail designs’) without any specific method or tool, and then assessed. However, in real design processes, the product can be further eco-improved (with the use of several techniques and tools) during the embodiment and detail design stages, and it is important to mention the explanation of what to do and how during this stage in an eco-design process.

Although the method suggests and describes a number of eco-design tools that can be used at each stage of the design process, it does not include eco-design guidelines, regulations and directives, which are very useful at the beginning of the design process so the product design specifications can be created. It is very important to consider these tools early in the design process when the concepts are not defined yet.

Another useful feature of this method and the manual that explains it, is that all the possible existing tools available are mapped in a diagram (Fig. 2.3) based on two criteria related with their use: 1) Complexity and time requirements and 2) Purpose of the tool. These support eco-design tools selection during the design process in an easy and flexible manner.

One of the problems of eco-design process methods which integrate eco-design tools is that they usually prescribe tools that were useful and relevant at the time the method was developed, and although some of them are still useful and valid, new more effective eco-design tools and easy to use may (and do indeed) appear rendering the old tools and techniques obsolete and no longer practical. For example, LCA-based software tools are becoming easier to use for non-LCA experts, making them more suitable than qualitative matrixes to assess the environmental impact of products, because matrixes are based on the subjective assessment of the professional who uses them, and LCA-based software tools carry out the assessment independently of the judgement, knowledge and skills of the user.

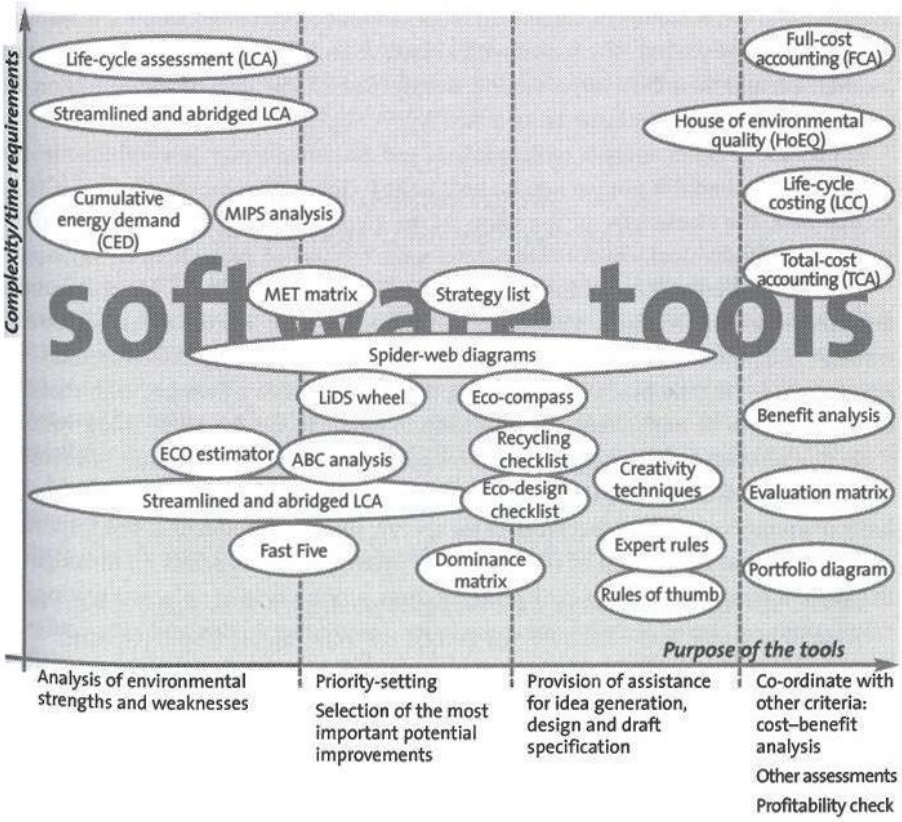


Figure 2.3. Eco-design tools diagram.

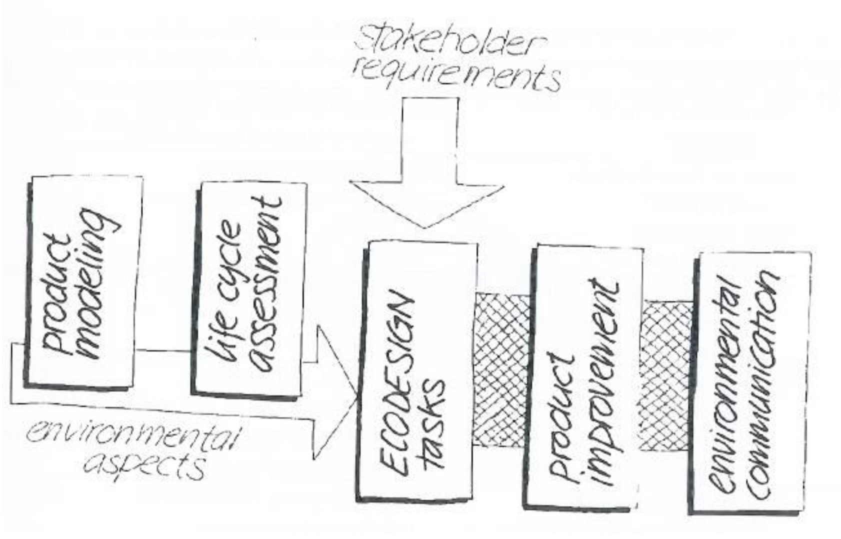


Figure 2.4. Wimmer and Züst eco-design method.

The eco-design method (Wimmer and Züst, 2002) described in the work published by Wimmer et al. (Wimmer et al. 2010), presents similarities with other eco-design methods, because it begins by assessing the environmental impact assessment of a reference product (Fig. 2.4 and 2.5). It assumes that the eco-design process begins with a product needing to be eco-redesigned. However, this is not always the case, especially when new products or have to be designed without any reference.

The process begins by 'modelling' the product (Fig. 2.4: 'product modelling') in order to obtain a deeper understanding of the qualities, performance and features of the product. Next, the environmental impact of the reference product is assessed. The results of this assessment together with the stakeholder requirements are then used to inform the eco-design strategies and design activities to be carried out to eco-redesign the product. The next stage (Fig.2.4: 'Product improvement') is related with the actual design activities, that comprise concept and embodiment design, followed by the communication of the environmental credentials of the eco-improved product. The step-by-step process is described in more detail in Fig. 2.5.

Step	*Leading questions*	*Tasks*	*Section*
1	What product is to be redesigned?	Describing the reference product with environmental parameters.	1.4
2	What are the stakeholder requirements? What is expected from the product?	Performing Environmental Quality Function Deployment.	3.3
3	What are the strengths and weaknesses compared with competitor products?	Environmental Benchmarking with the competitor's products.	3.4
4	What are the significant environmental aspects of the reference product throughout its entire life cycle?	Applying the ECODESIGN PILOT's Assistant or performing Life Cycle Assessment and interpretation of results.	3.5 or 2.3, 3.6
5	How to combine stakeholder requirements and significant environmental aspects into improvement strategies?	Deriving common ECODESIGN improvement strategies.	3.7.1
6	Which ECODESIGN guidelines should be implemented in the product?	Applying ECODESIGN PILOT's checklists to determine redesign tasks.	3.7.2 3.7.3
7	What are the environmental product specifications to start with?	Starting product improvement.	4.2
8	How to modify the functional structure of the product?	Adding new functions to and/or modifying functions of the reference product.	4.3
9	How to generate new ideas for the functions of the product?	Performing creativity session and/or searching for patents.	4.4
10	How to generate and select the best product concept variants?	Assembling ideas corresponding to each function of the redesigned product concepts and evaluate them against criteria.	4.5
11	How does the improved product look like?	Continuing embodiment design and layout, prototyping and testing.	4.6
12	How to communicate the environmental improvements of the product to the market?	Performing Environmental Product Declaration or self-declared environmental claims.	5.2

Figure 2.5. Wimmer and Züst eco-design method.

One of the key novel features of this eco-design method is the application during the design process of a web-based expert system (Ecodesign Pilot: Wimmer and Züst, 2002) that supports the process in different ways. This system can assist to: 1) Assess the product when a LCA is not possible due to limited resources or time constraints, and 2) Support the translation of environmental information into eco-design strategies, suggesting eco-design actions to the product developers to reduce the impact of the product based on the environmental information and stakeholder requirements. Although an expert system has obvious limitations, meaning, it cannot substitute an expert judgment and knowledge to decide what to do. However, it can support product developers with limited knowledge about eco-design to implement specific eco-design strategies to reduce the environmental impact of the product. The Ecodesign pilot expert system requires input about basic product features and performance, and provide an output based on possible eco-design strategies (and eco-design actions) to reduce the impact of the product. It can also assess (without much detail) the environmental impact of the product, providing a general idea about the product life cycle stages with the highest impact.

Expert systems in eco-design can be of great assistance, because they can support product developers with clear and unambiguous guidance about how to reduce the impact of a product without having to rely on their own (often) limited knowledge and subjective judgement with matrix-based tools such as the MET, MECO or ERPA.

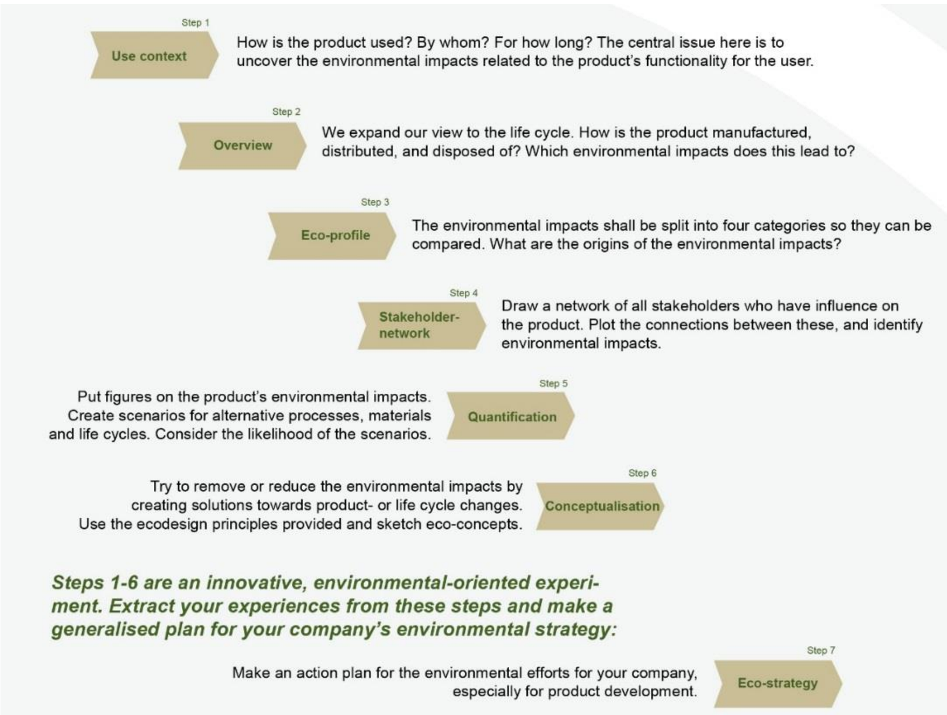


Figure 2.6. Mcaloone and Bey eco-design method.

The eco-design method developed by Mcaloone and Bey (2009), aims to create an eco-strategy that can be implemented in companies to reduce the environmental impact of the products manufactured (Fig. 2.6). However, the main focus of this eco-strategy is product development. Like other existing eco-design methods, it is based on the assumption that there is a reference product to eco-redesign, but it does not take into account a possible scenario where a new product has to be eco-designed without a reference.

The majority of the steps of the method are focused on studying and assessing the reference product, so there is only one stage (Fig. 2.6: Conceptualization) which concentrates on design-based activities, therefore the concept, embodiment and detail design stages processes are not explained.

Brezet and Van Hemel (1997) developed a manual to help companies integrate environmental issues in their procedures, and develop, manufacture and commercialize products with low environmental impact. The manual presents a step-by-step eco-design approach (Fig. 2.7) to develop eco-products. However, like many other eco-design methods developed assumes a reference product to begin with.

The method shown (Fig. 2.7) follows a very particular order which does not closely follow standard design process models stages. For example, step 1 (organising an eco-design project) is not a stage usually included in eco-design methods or design process models. Step 2 (selecting a product) is part of the definition of the Product Design Specification (PDS) of the new concept to be designed, usually this stage is called PDS. In step 3 (establishing an eco-design strategy) the results of the product reference assessment altogether with other type of assessments are used to identify the areas to be eco-improved with eco-design strategies. One of the advantages of this approach is that it also considers the marketing and launching the product, so it is more comprehensive than other eco-design methods.
Along with the approach, several tools are suggested at each design process stage to aid the product developer to assess, compare and improve the design solutions being designed along the process. Some of these tools are useful others are not. Tools for 'qualitative' assessment such as MET or MECO, as it has been explained before, do not support a product developer with no knowledge about environmental issues.

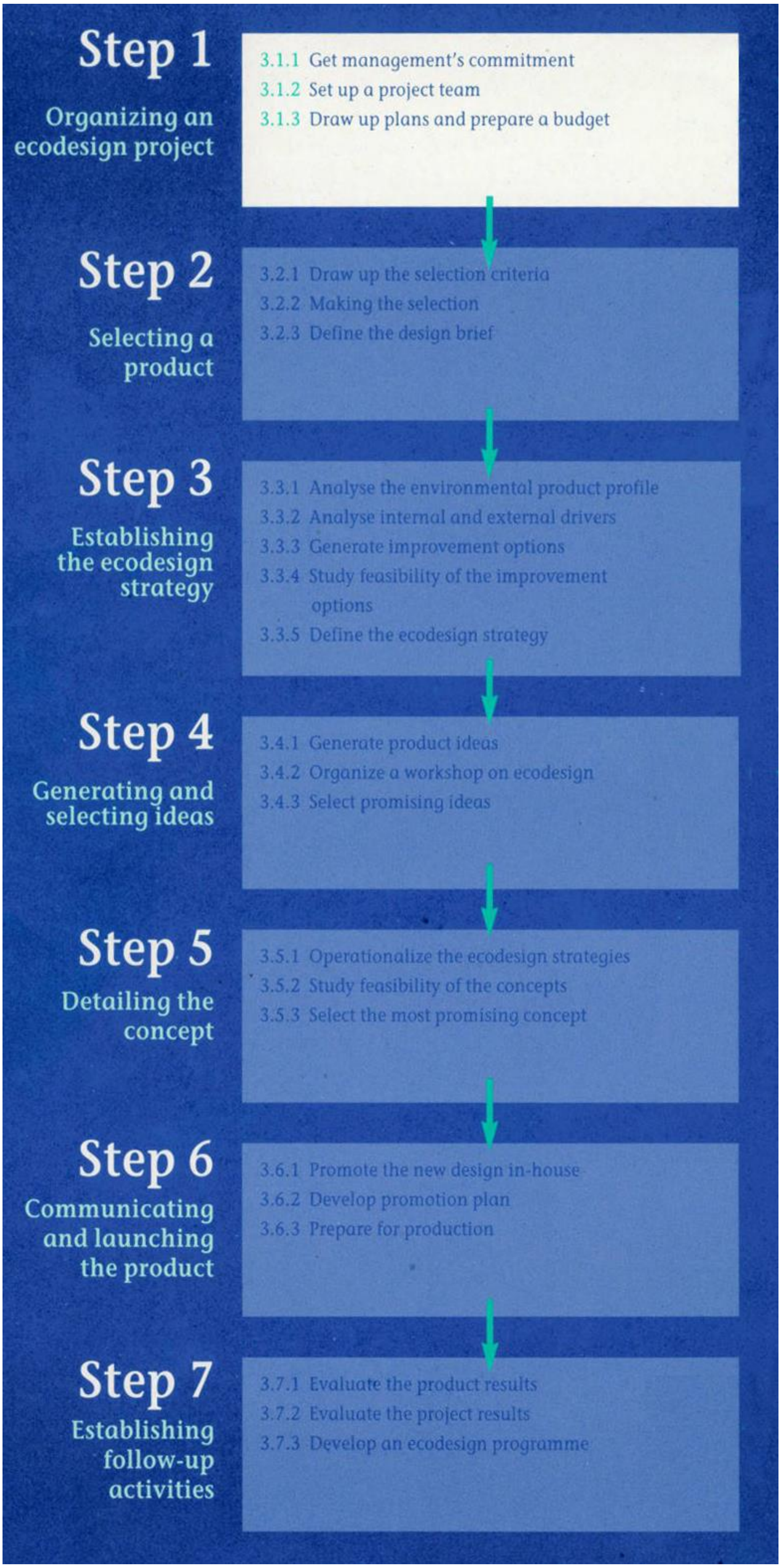


Figure 2.7. Brezet and Van Hemel eco-design method.

The criteria used in these tools to assess and compare products, and how the product developer judge and assess (providing a value) the product based on these criteria is totally subjective and strongly biased by user experience and knowledge about environmental impact assessment.

Some tools used in this approach, such as the ‘the eco-design strategy wheel’ are only useful to visualise a product’s current, desired and realisable environmental profile. However, this tool does not help to assess the environmental impact the product, or to suggest specific eco-design strategies to reduce specific environmental problems. The problem with this tool is that the values the user give to each criteria (e.g. Optimization of end-of-life system) are not based on objective measurement, but in subjective judgement grounded on the experience and knowledge of the product developer. The problem with ‘qualitative’ tools, is that they do not provide objective (free of interpretation) results, so the results may differ from user to user, confusing rather than helping the product developer to make design decisions based on an objective assessment.

The manual explains when the LCA method-tool can be used during the design process. It recommends to use the LCA at the beginning of the process to assess the reference product (if there is one) to establish the main causes of the environmental impact of the product, and also at the end of the design process to verify whether the planned objectives have been reached. The use of LCA is not recommended during the embodiment stage (mid process) because it may be too time consuming. Today’s LCA-based software tools have improved drastically since the development of the Brezet and Van Hemel manual (1997), and the databases contained in LCA-based software tools available today, are more extensive and with higher quality than previous LCA-based software versions, which means that to perform an LCA today can take less time, and provide more reliable results. As it will be shown later on, some of today’s LCA-based software tools can also be used during the concept and embodiment design stage to help decision making.

Step 1: assess environmental impacts

Step 2: research the market

Step 3: run an ideas workshop

Step 4: select design strategies

Step 5: design the product

Figure 2.8. Lewis and Gertsakis eco-design approach.

Lewis and Gertsakis (Lewis et al., 2001) present a general approach (rather than a step-by-step method) to design products with low environmental impact (Fig. 2.8). Like the majority of the existing methods and approaches, it assumes that there is a reference product that needs to be assessed and eco-improved, but it does not explain how to eco-design a product without a reference. In addition, it does not explain in much detail the steps to be carried out during the concept, embodiment and detail design stages. It just mentions one stage where ideas are developed (Fig. 2.8: 'run an ideas workshop'), but the aim of this stage is to build the briefing or specification of the product, which is designed in the next step (Fig. 2.8: step 5: design of the product).

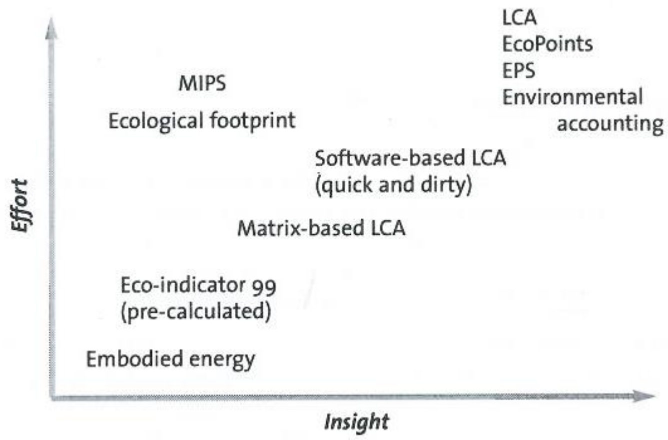


Figure 2.9. Lewis and Gertsakis eco-design approach.

In the manual that explains this approach, there is also (Fig. 2.9) a diagram where the tools are classified based on the effort (time-expertise) it takes to use them versus the insight (quantity-quality of results) they provide during the assessment. This is useful in order to know which type of tool to use depending on the particular situation-application, which is conditioned by the expected results, time available, budget and expertise of the user.

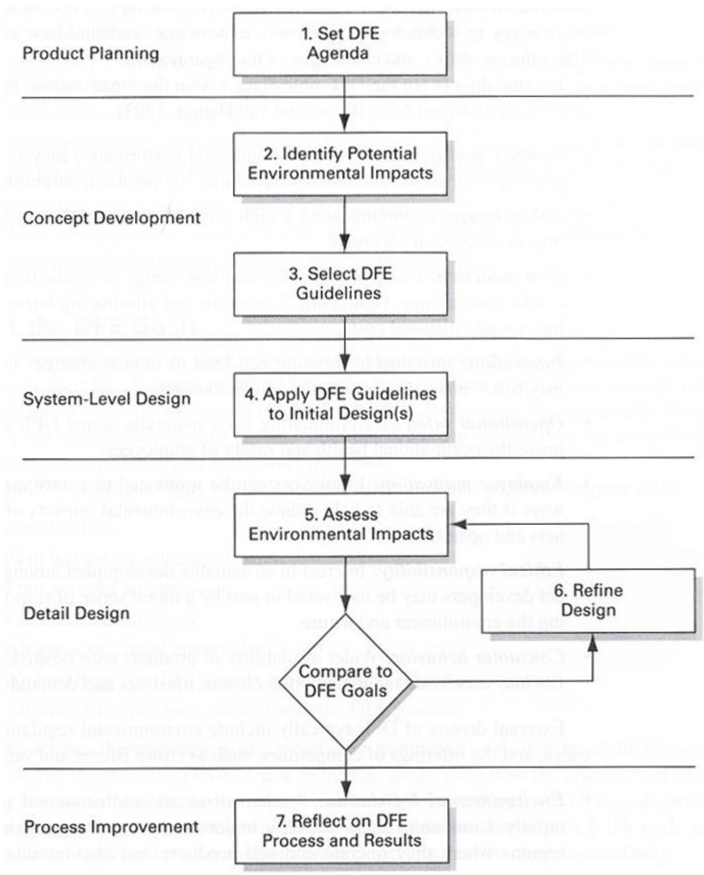


Figure 2.10. Ulrich and Eppinger eco-design method.

Ulrich and Eppinger's (2008) eco-design method (Fig. 2.10) shows a design process with stages similar to the ones found in typical design processes, although some stages are given different names: 'Product planning' corresponds to the definition of the briefing or product design specifications, 'concept development' to concept design, 'system-level design' to embodiment design, and 'process improvement' to the final product (results). In each of these stages, several types of eco-design activities are performed.

This method is general and does not explain the eco-design activities in detail. At the beginning of the process, the first eco-design activity is 'to set the DfE agenda', which is assumed to be related with the eco-design specifications of the product. During the 'concept development stage', the potential environmental impacts of the product (product life cycle stages and components) are identified, however the method does not explain how (i.e. which tools have to be used to assess the environmental impacts). In addition, at this stage, 'DfE guidelines are selected' in order to reduce the impact identified in the previous stage. During the 'systems level design' stage, Design for Environment (DfE) guidelines are applied, and during the detail design stage the product is assessed to verify if the environmental goals have been achieved, if not, the product is refined and assessed again until the DfE goals are achieved. Finally, the last stage 'process improvement' reflects on the DfE process and results, which is not a stage typical in design processes.

Although some of the eco-design activities executed are also used in typical eco-design processes, for example, assessment of reference product, selection and application of eco-design strategies, assessment of the designed product and a new iterative loop with refinements if the product does not achieve the DfE goals, the order in which these are included in the design process stages does not follow the typical pattern described in other design processes. For instance, the application of DfE guidelines (strategies) is also usually done at the concept design stage, and the assessment of the product can also be conducted at the concept design stage, but usually the type of assessment and the tools used are different from the ones used in the detail design stage. Assessment and comparison of developed solutions with the DfE goals (product specifications) are carried out at the concept, embodiment and detail design stages, depending on time and resources of the product development team. During the whole process DfE (Design for the Environment) is used, which is the American term for Ecodesign, which is usually more commonly used in Europe.

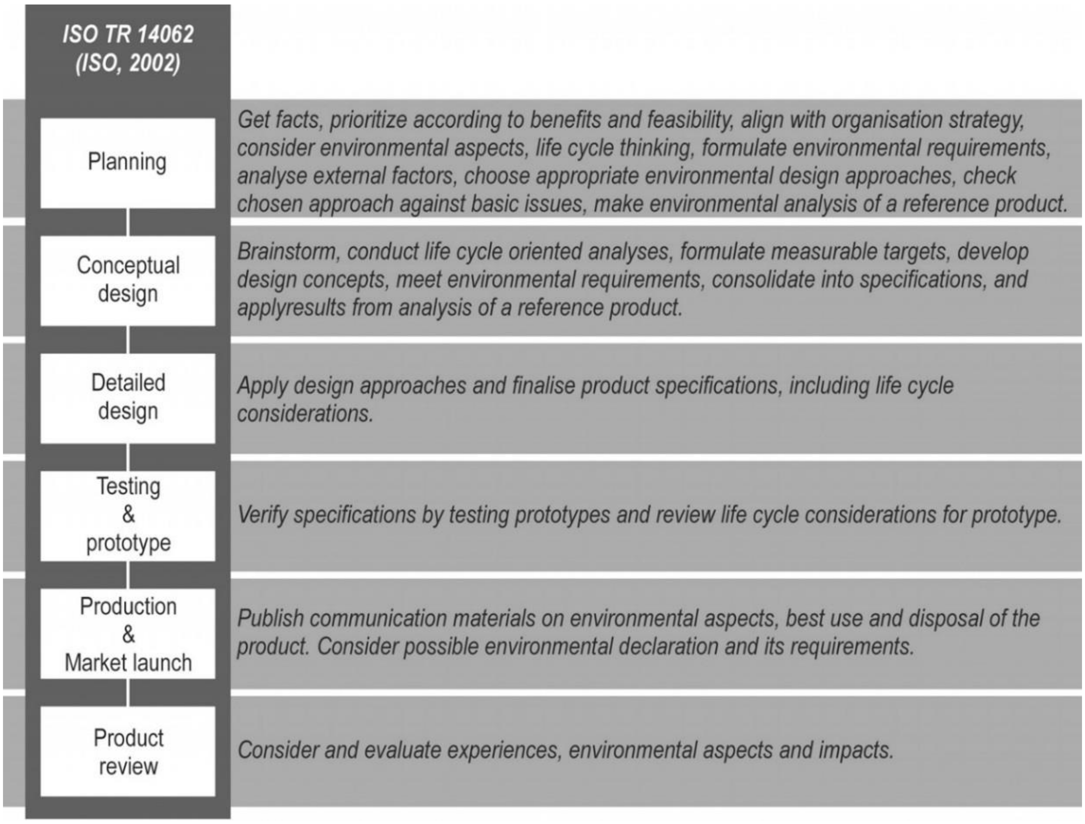


Figure 2.11. ISO TR 14062 eco-design method.

The ISO TR 14062 (ISO, 2002) describes the eco-design activities to be carried out at each stage of the design process in general terms (Fig. 2.11).

This method describes the design process and prescribes what design actions to execute, when and with which tools in a general manner, which leaves the model open and flexible to suit different eco-design processes depending on the time and resources (such as skills, available tools) of each product development team. Customisation is a key issue if eco-design models wish to be used and implemented, as it is shown in the next eco-design design process models from two companies (Motorola and Alcatel), which have their own customised eco-design process models adjusted to their resources and needs.

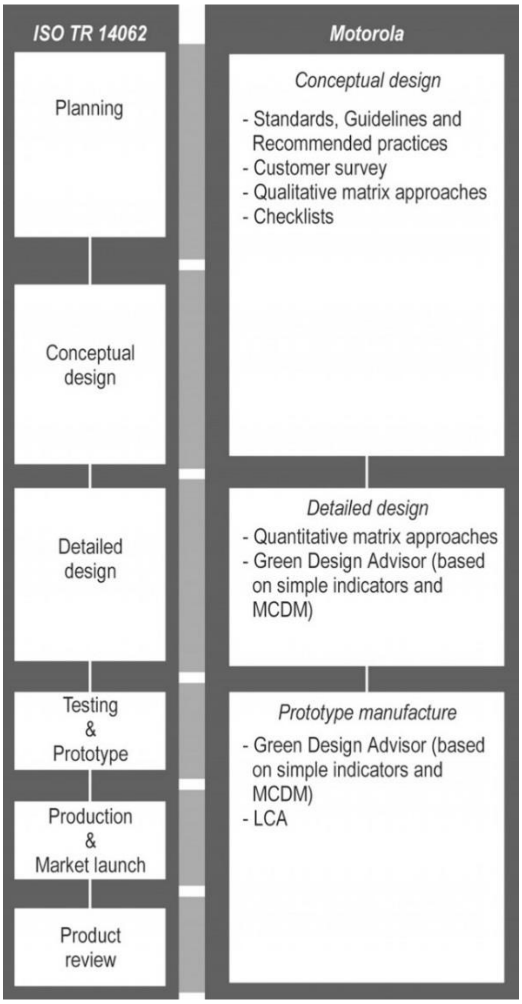


Figure 2.12. Motorola - eco-design method.

The eco-design process of Motorola (Mueller and Hoffman, 2000) explains what type of eco-design tools have to be used and when (Fig. 2.12). During the early stages of definition of the concept, eco-design guidelines, checklists, regulations, standards and recommended practice are used to inform the specifications of the concepts. In addition, 'qualitative matrix-based approaches' are also employed to assess and compare the different concepts developed. During the detail design stage when the product is more defined and there is more information about it, quantitative matrix-based approaches are used to assess (more accurately) and compare different design options. At this stage is also used the 'Green design advisor' to aid with selection of materials, and manufacturing processes of low environmental impact, and also to assess different concepts and solutions. In the last stages: 'Testing and prototyping', 'production and market launch' and 'product review', it is used 'Green design advisor' and LCA. These types of tools are used (LCA in particular), because a lot of (if not all) information about the product is known at this stage, so it is possible to do an LCA. Also, at this stage the product is finished and LCA results are required if environmental information (EPS, and eco-labels) want to be provided to customers.

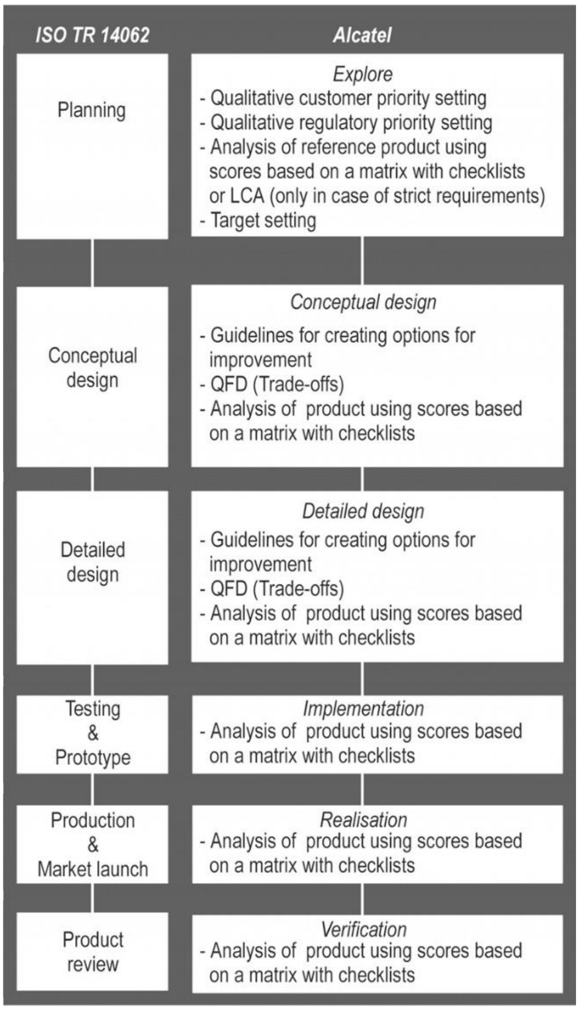


Figure 2.13. Alcatel - eco-design method.

The eco-design process of Alcatel (Bervoets et al., 2000), shows the type of eco-design tools that have to be used, and when these should be used during the design process (Fig.2.13). During the early stages of the process the product initial specifications are informed with: 'qualitative customer priority setting', 'qualitative regulatory priority setting', 'analysis of reference product with LCA' (if strictly required), and 'target settings'. In the model, it is explained that the LCA of the reference product should only be conducted if strictly necessary because it is a time consuming activity requiring specific expertise. Instead of using LCA, assessment is carried out with matrix-based checklists that can provide some general idea of the environmental impact of the product in less time, by non-LCA experts. It is important to highlight that the use of matrix-based checklists is not wrong in itself, the criticism of current matrix-based tools is due to the type of *criteria* used in the matrixes, which is difficult to assess by non- environmentalist/LCA experts.

During the concept and detail design stages, 'guidelines', 'Quality Function Deployment (QFD)' and 'matrix-based assessments' are used to guide the selection of the solution with the lowest environmental impact possible.

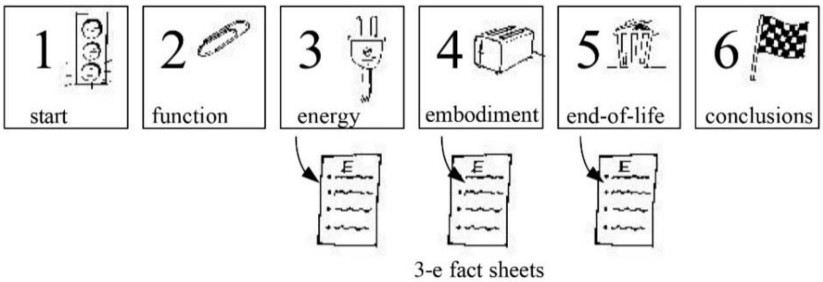


Figure 2.14. The EPAss method.

Jansen and Stevels' (1998) Environmental Product Assessment (EPAss) method (Fig. 2.14) is mainly focused on the assessment of a product. Although the authors states that the aim of the method is to assess the environmental impact of a product, many steps required during the method are based on the assessment of the performance and function of the product, which may not have an indirect effect of the environmental impact. For example, in step 2, it is required to define an input-output diagram, which is not needed to perform an LCA or other type of environmental impact assessment.

The method is divided in two main phases: Assessment (steps 1-5) and selection of eco-design strategies (step 6). However, all the initial steps (steps 1-5) are not necessary and/or helpful in discovering the life cycle stages or components with higher environmental impact so these can be eco-improved with eco-design strategies (step 6). Although it is necessary to study and assess the product before an environmental impact assessment can be completed, the information needed to do this is very specific, and is usually related with the information that will be required to conduct the LCA or other specific assessments such as disassembly, or energy used. The initial assessment requires the following information: Life cycle process diagram of the product, Energy and/or other resources consumed during use, expected lifetime, disassembly of the product (and packaging if included) to obtain Bill of Materials (BoM), time-easiness of disassembly, and possible end of life scenarios. All this information will be used to complete a qualitative, or quantitative environmental impact assessment such as an LCA. This method therefore, presents some steps which are not necessary for the environmental impact assessment of the product. In addition, an additional step should be included with an environmental impact assessment (quantitative/qualitative) before step 6. An important feature of the method is that the proposed eco-design strategies to be implemented in step 6 to reduce the environmental impact of the product are not only considered based on environmental impact but also with additional criteria such as consumer benefits, company value, and technical feasibility (Fig. 2.15), which may help to prioritise when it is not possible to implement them all due to time, cost, or product architecture incompatibility (i.e. two eco-design strategies are in conflict).

green options	Environm. Benefit (mPts)	consumer benefit		Company value		company investments	technical feasibility
		price	other	Production costs	other		
1							
2							
:							
n							

Figure 2.15. The EPAss method – Table used in ‘step 6: conclusions’.

Nielsen and Wenzel’s eco-design process model (Fig. 2.16) is the result of the EDIP project (Wenzel, Hauschild and Alting L, 1997) which was aimed to develop a method to assess the environmental impact of products. The method is based around the use of the LCA tool, and it is one of its main advantages. From the beginning of the process, an LCA model of the reference product is built, and it is used for assessment and comparison until the end of the design process. The LCA model is input with more or less complete and accurate data depending on the data available at each stage of the design process, and the information provided at each step. Unlike the qualitative assessment methods such as MET, MECO, and other similar tools, this tool is objective, reliable, and does not depend on the subjective judgement (based on experience) of the product developer. One of the main drawbacks of this method is the fact that the assessment and comparison of the product and design solutions, since is based on LCA, is time consuming and requires specific knowledge about LCA.

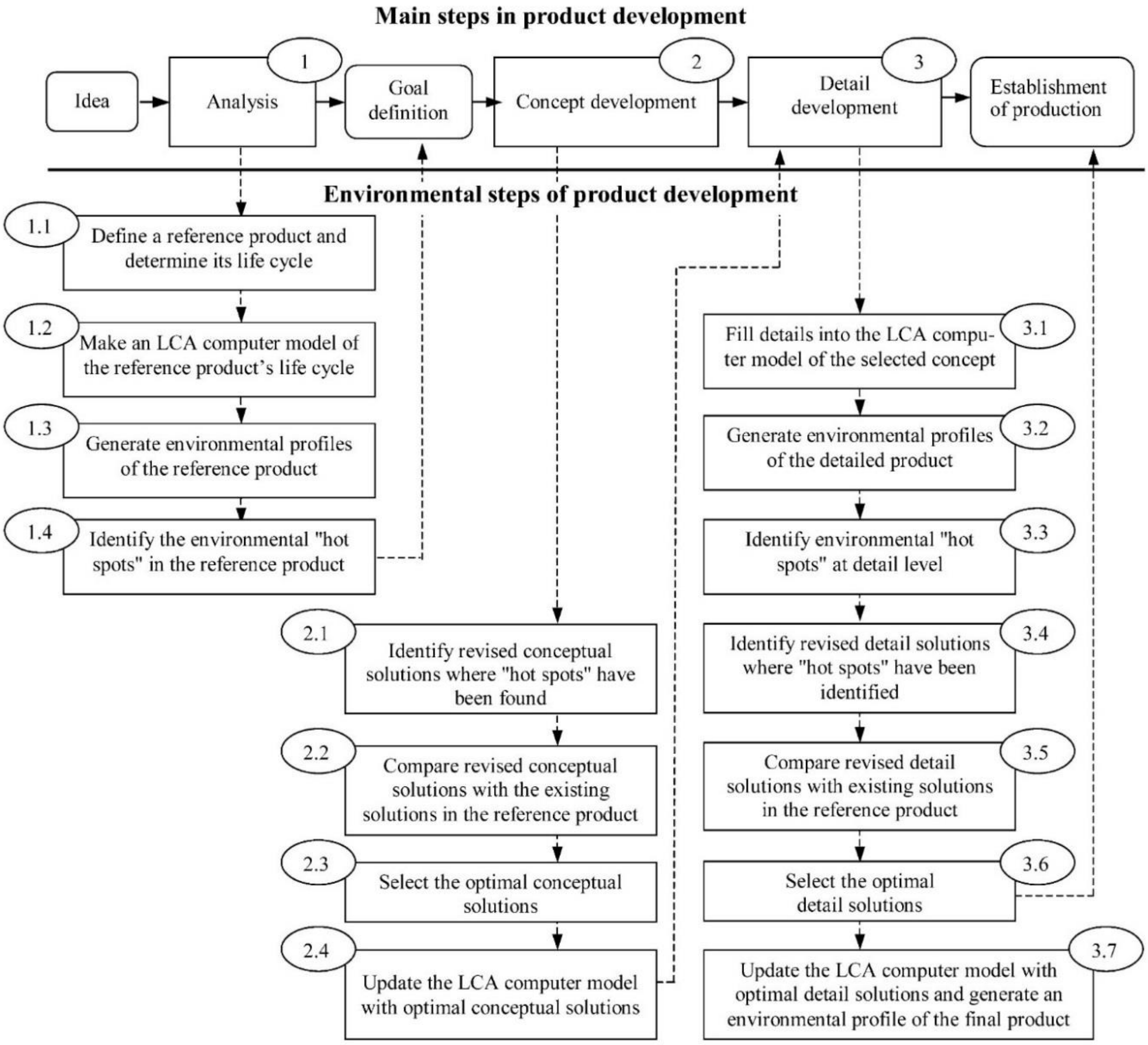


Figure 2.16. Nielsen and Wenzel method.

Nevertheless, once the initial LCA model of the reference product is built, the changes that have to be made in the LCA to assess different versions (using what if scenarios) takes much less time than a complete LCA model, and has the advantage that at the end of the process a complete LCA model is already built to provide a complete environmental profile of the product for eco-labelling or EPD purposes.

Like other eco-design methods, it assumes that there is a reference product that needs to be eco-redesigned, however it does not explain how to begin an eco-design process when a reference product is not considered.

The method does not apply eco-design tools such as guidelines, and it does not take into account the limitations of the LCA tool for the complete environmental impact assessment of a product. LCA can provide a quantitative environmental impact assessment of a product based on the assessment of the materials and industrial processes used during its lifecycle, but it cannot evaluate product features like disassembly, modularity, or light control to name a few, which can indirectly affect the environmental impact of the product.

All the eco-design methods developed and described in this section can aid the product developer to reduce the environmental impact of products. However, some of them have areas that can be improved. In addition to this, some of them need to be updated with the last eco-design tools and techniques developed, which in some cases are more efficient/. During the eco-design of the lighting product in the case study (chapter 4), some elements from these methods have been taken into account and integrated, and others ignored based on the trial of the author of these tools and methods during the case study.

2.2.2 - Eco-design models for lighting products

There are no specific eco-design methods to design lighting products to date. Schmalz and Boks (2010) conducted a study about how to reduce the environmental impact of lighting products focused on user behaviour, but this was not an in-depth study and focused only on design for sustainable behaviour, that is, how to reduce the environmental impact of lighting products by modifying user behaviour when using the product through design features designed (scripted) in the product.

The only existing studies about methods to design eco-lighting products have been carried out by Casamayor and Su (2010a, 2010b, 2011a, 2011b, 2013). However, these studies

present early incomplete findings about specific issues related with this area, and do not present and evaluate a final integrated approach.
It is probable that some companies are using in-house eco-design methods and/or tools to eco-design LED lighting products, but these have not been disclosed to the public outside the companies, so they are not available to use or review.

This research aims to contribute to the body of knowledge of this area with the study, development and evaluation of an integrated approach to eco-design lighting products, in a real world industrial context.

2.3 - Directives and regulations

There are mandatory directives and regulations that need to be considered in the eco-design process of lighting products.

The Energy labelling directive 2010/30/EU (European Commission, 2015a) specifies the lamp energy efficiency class the luminaire is compatible with, and the energy efficiency class of the light source used. The Eco-design directive (2005/125/EC), (European Commission, 2005), aims to reduce (at the design stage) the energy consumption and other negative environmental impacts of products. The Waste Electrical and Electronic Equipment recycling WEEE directive (European Commission, 2012) requires producers and distributors to finance the collection, treatment and recycling or reuse of Electrical and Electronic Equipment, with the objective to encourage the separate collection and subsequent treatment, reuse, recovery, recycling and environmentally sound disposal of WEEE. The Restriction of Hazardous Substances (RoHS) directive (European Commission, 2011) restricts the use of six hazardous substances: Lead (Pb), Mercury (Hg), Cadmium (Cd), Hexavalent chromium ($Cr6+$), PolyBrominated Biphenyls (PBB) and PolyBrominated Diphenyl Ether (PBDE), in products. The Energy-related Products (ErP) Directive 2009/125/EC (European Commission, 2009a) aims to improve energy efficiency and environmental protection. This applies to products that use energy consumption throughout their life cycle. The Packaging and Packaging waste directive (European Commission, 1994) affects any type of product that uses any type (primary and secondary) of packaging. Its main objectives are: Reduce packaging material excess, avoid specific hazardous substances, inform the consumers about the content of product and packaging, reduce the amount of waste at the end of life of the packaging, increase the re-use and recycle of packaging waste and inform the manufacturer about their responsibility to recuperate and recycle its packaging.

The IEC 62430:2009 standard of 'Environmentally conscious design for electrical and electronic products' (IEC, 2009c) applies to all the electrical/electronic products, and therefore also applies to lighting products. This international standard provides a set of requirements for the process of environmentally conscious design reflecting the contents of IEC Guide 114 and ISO/TR 14062. This International Standard is intended for use by all those involved in the design and development of electrical and electronic products. To ensure consistency throughout the electro-technical sector the use of this standard as a base reference is encouraged.

2.4 - Eco-design tools

The main difference between eco-design methods and traditional design methods is that eco-design methods also take into consideration the environmental impact of the product during the design process. Traditional design methods and the tools used within them do not help product developers to assess and reduce the environmental impact of products. This is why additional specific tools (eco-design tools) have to be integrated in traditional design processes.

There are many types of eco-design tools, and each of them can be used for different purposes. These can be classified based on different criteria, and some authors (Bovea and Perez-Belis, 2012; Dewulf, 2003) have conducted extensive reviews of the different types of eco-design tools available based on different criteria. In this literature review, eco-design tools will be classified in six main categories based on their purpose:

- Guidelines and checklists.
- Environmental impact assessment tools.
- Databases.
- Tools to improve the reliability of the product.
- Tools to communicate the environmental profile of the product.
- Tools to select materials, components and processes.

This section (section 2.4: Eco-design tools) is divided in fourteen additional sub-sections: Section 2.4.1 (Eco-design guidelines and checklists); section 2.4.2 (Environmental impact assessment tools); section 2.4.2.1 (Qualitative – Environmental impact assessment tools); section 2.4.2.2 (Quantitative – Environmental impact assessment tools); section 2.4.2.2.1 (LCA tools); section 2.4.2.2.1.1 (LCA and LED-based lighting products); section 2.4.2.2.2 (LCA-based software tools); section 2.4.2.2.2.1 (Integration of LCA-based software tools in the design process); section 2.4.2.3 (CAD tools with LCA integrated); section 2.4.3 (Databases); section 2.4.4 (Tools to improve the reliability of the product); section 2.4.5 (Tools to communicate the environmental profile of the product) and section 2.4.6 (Tools to select materials/components).

Section 2.4.1 reviews the eco-design guidelines and checklists related with eco-design; section 2.4.2 reviews the tools available to assess the environmental impact of products. This section (2.4.2) is divided in several additional sub-sections which reviews: tools that can assess the environmental of products qualitatively (section 2.4.2.1); tools that can assess the environmental impact of products quantitatively (section 2.4.2.2); and CAD tools with LCA integrated (section 2.4.2.3). The section of tools that can assess the environmental impact of products quantitatively (section 2.4.2.2) is divided in: section 2.4.2.2.1 (LCA tools) which reviews the tools that are based on the LCA method, and its relation with LED-based lighting products (section 2.4.2.2.1.1), and section 2.4.2.2.2 (LCA-based software tools) which reviews the software tools based on the LCA method, and the integration of these in the design process (section 2.4.2.2.2.1). Section 2.4.3 (Databases) reviews the databases that contain the datasets and inventory of materials and processes, which are usually used in LCA. Section 2.4.4 (Tools to improve the reliability of the product) reviews the tools used to improve the reliability of the product to extend its lifespan. Section 2.4.5 (Tools to communicate the environmental profile of the product) reviews the tools used to inform the consumer about the environmental credentials of the product, and section 2.4.6 (Tools to select materials, components and processes) reviews the tools available to aid the product designer to select the materials, components and processes with the lowest environmental impact.

Section 2.4.4 (Databases) is reviewed in more detail in Appendix 2.1.

2.4.1 - Eco-design guidelines and checklists

Eco-design guidelines and checklists are tools used in eco-design processes to provide best practice generic rules that can be applied at each product life cycle to reduce the environmental impact of the product. Some of these are generic, and some product specific. In this research, the ones that apply to lighting products have been considered. Eco-design guidelines can be used when there is no reference product at the beginning of the design process, or when specific eco-design features have to be included in the design brief or Product Design Specifications (PDS).

Eco-design guidelines can be 'converted' into checklists so they can be used during the design process to check if the eco-design guidelines stated in the Product Design Specifications (PDS) are achieved during the design process.

There are many handbooks and manuals that provide eco-design guidelines and checklists to reduce the environmental impact of products. Some of these manuals are from companies that developed their own guidelines (Meinders, 1997; Nordkil, 1998; Siemens, 2004) for internal use and became popular and used outside the company, others are generic guidelines and checklists that can be found in publications: books and papers (Brezet and Van Hemel, 1997; Chitale and Gupta; Giudice, et al., 2006; Lewis, et al., 2001; Luttropp and Karlsson, 2001; Shedroff, 2009; Tischner et al., 2000; UNEP and TU Delft, 2006; Vezzoli and Manzini, 2008; Yarwood and Eagan, 1998) written by academics and experts in the area of eco-design and sustainable design.

Below are the criteria from the eco-design guidelines relevant to lighting products (including its packaging). These have been collated from different publications and manuals available in the literature:

- Use fewer components.
- Design components with several integrated functions.
- Increase product lifespan.
- Apply modular design.
- The product should be easy to repair.
- The product should be easy to upgrade.

- Specify re-manufactured and re-used components.
- The product should be durable.
- Easy access to components for repair.
- Avoid manufacturing processes that consumes a lot of energy.
- Avoid distribution processes that consume a lot of energy.
- Avoid materials that consume a lot of energy to extract and process.
- Improve the energy-efficiency of the product system.
- Design and implement systems that facilitate products and components recovery for re-use/re-manufacturing/recycling.
- Use the minimum type of different materials.
- Specify highly recyclable materials.
- The product should be easy/fast to disassembly.
- Avoid the use of (special) tools for disassembly.
- Avoid non-detachable joints (welded or glued joints).
- Avoid the use of labels.
- Avoid the use of finishes in materials.
- Specify snap-fit joints.
- Select low environmental impact materials and manufacturing processes.
- Avoid the use of PVC.
- Reduce the weight and volume of the product and packaging.
- Specify standard components
- Specify reliable components from well-known suppliers.
- Optimise use of material.
- Specify Zhaga components.
- Use smart technology that reduces energy during use (i.e. occupancy and light sensors, timers).
- Allow light control (intensity/direction): Use dimmers and directional lights.
- Use energy-efficient light sources.
- Specify recycled materials with the highest % of recycled material.
- Reduce the number of joints.
- Mark materials for easy identification for recycling.
- Mark products/materials that can be recycled.
- Avoid PCB with welded components.

- Integrate functions.
- Specify drivers with short and open circuit protection.
- Specify drivers with overload and over voltage protection.
- Specify drivers with Safety Extra Low Voltage (SELV).
- Specify future-proof drivers that provide industry leading output voltage range enabling seamless support of LED generations.
- Simplify the manufacturing process, fewer processes.
- Implement long term warranty.
- Provide exploded view with components and suppliers of each component to facilitate repair.
- Provide information about how and where to dispose the product.

The eco-design guidelines mentioned above can be applied at all design stages of the design process, although these are usually used at the beginning of the process. These can also be used as checklists at each stage of the process to check and ensure the product fulfil the specifications set in the Product Design Specifications (PDS).

Eco-design guidelines can become checklists when used with different format, in this sense, all the guidelines mentioned above can be used as checklists. The checklists that are more relevant for lighting products are explained below.

<u>WEEE/RoHS directives checklist (Centre for Sustainable Design, 2015)</u>:

This checklist (Fig. 2.17) has been created to assess if the product complies with the WEEE and RoHS directives. It is a checklist based on a 4x4 matrix. In the Y axis there are questions or issues about four areas: General (is the type of product or end application covered by the WEEE and RoHS Directives?), RoHS directive, and WEEE directive. In the X axis there are four possible answers to the questions/issues raised: Yes, No, N/A, and comments.

Questions/issues	Y	N	N/A	Comments
General				
1 Is the product or end application covered by the WEEE and RoHS Directives?				
a) Product or end use of components / sub-assemblies which falls under one of the following applications and not rated greater than 1000V ac or 1500V dc) o Large household appliances o Small household appliances o IT equipment o Telecommunication o Consumer equipment o Lighting equipment o Electrical and electronic tools o Toys, leisure and sports equipment o Medical devices (except implanted and infected products) o Monitoring and control instruments o Automatic dispensers				
b) Does the product contain, or potentially contain the following materials (not exempted under the RoHS Annex) o Lead (See 4.4 for exemptions) o Mercury (See 4.4 for exemptions) o Hexavalent chromium (See 4.4 for exemption) o Cadmium (See 4.4 for exemption) o PCBs o Polybrominated biphenyls (PBB) o Polybrominated diphenyl ether (PBDE) o Radioactive substances o Asbestos c) Do plastic parts weigh more than 25grams? - (require materials coding)				
d) If the product can fall into the class of separately collected, does the product contain any of the following listed in Annex II of WEEE, which will be required to be removed from the product at end-of-life for separate treatment. o Fluids o Polychlorinated biphenyls (PCB) containing capacitors. o Mercury containing components, such as switches or backlighting lamps o Batteries. o Printed circuit boards of mobile phones. o Other printed circuit boards greater than 10 square centimetres. o Toner cartridges, liquid and pasty, as well as colour toner. o Plastic containing brominated flame retardants. o Asbestos waste. o Cathode ray tubes. o Chlorofluorocarbons (CFC), hydrochlorofluorocarbons (HCFC) or hydrofluorocarbons (HFC), hydrocarbons (HC). o Gas discharge lamps o Liquid crystal displays (together with their casing where appropriate) of a				

surface greater than 100 cm2 and all those back-lighted with gas discharge lamps. o External electric cables o Components containing refractory ceramic fibres as described in Commission Directive 97/69/EC of 5 December 1997 o Components containing radioactive substances.				

Figure 2.17. WEEE/RoHS directives checklists.

The Econcept eco-design checklist (Tischner et al., 2000):

This checklist (Fig. 2.18) is based on a 6x5 matrix. In the Y axis there are questions or issues grouped in 5 sections (extraction of materials and choice of raw materials, production, use and service, reuse or recycling, and final disposal) of the product life cycle. In the X axis there are 4 evaluation scores (+, +/-, -, 0) and an additional area for remarks/comments. The scores correspond to: + = good solution, +/- = indifferent, - = bad solution and 0 = not relevant. The aim of this tool is to assess and compare the environmental impact of the concepts to aid in the selection of the best concepts, taking into account the whole life cycle

However, some of the questions (Example: Fig. 2.18: avoiding emissions: For example, by refinement procedures) are still difficult to answer by a product developer with no expertise in environmental issues or when concepts are not defined enough to know all the information requested.

Extraction of raw materials, choice of raw materials + +/- - o remarks:

- minimising material input
- minimising energy input
- minimising land use (raw materials extraction, production)
- avoiding input or emission of hazardous substances
- avoiding emissions (e.g. by transports)
- minimising waste production, recycle materials
- preferring regional raw materials
- using renewable raw materials produced by sustainable methods
- using socially acceptable substances that will pose no health hazards
- using recycled materials

Production + +/- - o

- minimising material input
- minimising energy input
- minimising land use
- avoiding input or emission of hazardous substances
- avoiding emissions (e.g. by refinement procedures)
- minimising pre-consumer waste production, recycle materials
- preferring regional suppliers along the whole supply chain
- minimising packaging
- using renewable ancillary materials produced by sustainable methods
- using socially acceptable processes that will pose no health hazards

- minimising land use (raw materials extraction, production)
- avoiding input or emission of hazardous substances
- avoiding emissions (e.g. by transports)
- minimising waste production, recycle materials
- preferring regional raw materials
- using renewable raw materials produced by sustainable methods
- using socially acceptable substances that will pose no health hazards
- using recycled materials

Use / service + +/- - o remarks:

- creating excellent customer benefits
- appropriate design for target group
- minimising complaints and returns
- keeping service available

The following alternative strategies might be discussed

- design for longevity (strategy 1)
  - timeless design
  - 'long life' guarantee
  - robust, reliable wear-resistant design
  - design for easy repair and maintenance
  - possibilities of combination
  - variability, multifunctionality
  - possibility of re-use and shared use
  - design for update to the best available technology

or

- design for short-lived products (strategy 2)
  - fashionable design
  - design for product take-back
  - design for recycling
  - design for environmentally-friendly disposal, e.g. compostable

- understandable design for the user
- design for self controllable and optimisable functions
- dirt-resistant, easy to clean design
- minimising material and energy input during use
- avoiding input or emission of hazardous substances

Figure 2.18. Econcept Eco-design checklist.

Philips Fast Five checklist (Meinders, 1997):

This checklist (Fig. 2.19) is based on a 5x2 matrix. In the Y axis there are questions grouped in 5 categories (energy, recyclability, hazardous waste content, durability-reparability-preciousness, and alternative ways to provide service) and in the X axis there are 2 possible answers to the questions or issues raised: Yes/No. The results can be interpreted as follows: 5 ‘yes’ means an excellent option, 4 ‘yes’ means probably a viable choice, 3 ‘yes’ means an interesting alternative, but can be improved, 2 ‘yes’ means reconsider the reference concept, 1 ‘yes’ upgrade the reference, 0 ‘yes’ a bad option.

This tool is suitable for eco-redesign of products where a reference product needs to be re-designed, or to compare new developed products with other reference products.

This tool is useful to compare different design solutions, but the disadvantage is that, like other checklists, ask general questions which are not easy to answer. For example: in category 4: it says ‘does the proposed product has better durability, reparability or affection level than the reference product?’ However, this is not easy to quantify objectively. It would rather be more useful to ask questions such as: How many years of warranty? or Does it feature modular design for upgrade? What is the technical lifespan of the product or its key components?

Product/Project	Person in charge	Date
Categories of questions		Yes or No ?
Category 1 – Energy **Does the proposed design require less energy than the reference counterpart?** Consider manufacturing, transportation, product use (both in normal operation as well as in stand-by mode		
Category 2 – Recyclability **Is the proposed product more recyclable than the reference product?** Consider whether the larger components can be easily separated into mono-material sub-assemblies. Special care should be given to the separation possibilities of non-compatible metal or plastics. What is the amount of actually recycled material in the product?		
Category 3 – Hazardous waste content **Does the product design contain and/or produce less chemical waste than the reference alternative?** Consider whether any restricted materials are used, e.g. halogenated flame retardants, cadmium pigments, or ozone depleting chemicals (ODCS)		
Category 4 – Durability, reparability and preciousness **Does the proposed design have better durability, reparability or affection level than the reference product?** Consider whether the new design will last longer or be easier to upgrade than the reference. Also consider whether the precious qualities of the new design will make the owner/user keep the product longer than the reference.		
Category 5 – Alternative ways to provide service? Are there ways to provide the service that produces lower ecological load? Consider whether there are techniques that require much less energy or material, but provide the service at the same level of quality		

Figure 2.19. Philips fast five checklist.

Checklist for recyclable joint engineering (Brinkmann et al., 1994):

The aim of this checklist is to assess the recyclability and ease of separation of products' parts/components connected by joints. It is a checklist based on an 8x3 matrix (Fig. 2.20). In the Y axis there are questions related to joints (i.e.: Are they easy to find, separate, access? number of connections used, diversity of connections used and tools required to dismantle, need of tools and automation of dismantling process). In the X axis there are 3 evaluation scores: Ideal, Acceptable and Need for action.

This checklist can be used to indicate the recyclability of a product during the design process stages. Although the questions asked are straightforward (interpretation free) and easy to answer by a product developer with no experience in environmental issues, it is stated that products that have to be 'dismantled by hand' need action. Today, the majority of the products, involve some initial partial manual dismantling, and some require full manual dismantling before mechanical dismantling (shredding). In the cycled project

(2015), nearly all the lighting products dismantled had to be partially or fully dismantled manually. This means that although automatic disassembly is a much better solution, it is also very rare, so manual dismantling cannot be considered the worst case scenario (need for action) when it is one the most used and only method (in some cases) to recuperate the materials nowadays. This checklist might need to be updated with recent data about recycling centres processing techniques in order to be applicable today.

Responsible: Date:	Product:					
Joint engineering	**Assessment and what to do (mark the appropriate box)**					
	Ideal		**Acceptable**		**Need for Action**	
Easy to find?	Obvious?		Covered?		Hidden?	
Separability? (ease of separation?)	Separable without destruction?		Separable by destroying the connecting elements?		Separable by damaging the component?	
Accessibility?	Axially accessible, in direction of dismantling?		Axially accessible?		Radially or otherwise difficult to access?	
Number of connecting elements	One/ few connections?		Few, due to functional limitations?		High?	
Diversity of connections and tools	Uniform connection elements		Standardised within each type of connection (one type of screw, one type of snap fitting)?		Zero or negligable standardisation?	
Need of tools	Separable without tools?		Separable with a common tool?		Separable with a specific tool?	
Automatisation of dismantling process	Automatisation?		Mechanical dismantling?		Dismantling by hand?	
Subtotal of marks	Ideal		Acceptable		Need for action	

Figure 2.20. Checklist for recyclable joint engineering.

2.4.2 - Environmental impact assessment tools

Environmental impact assessment tools consider the full life cycle of products and systems in the assessment. These tools adopt a holistic life cycle approach that assess products and systems from extraction of materials to the End of Life (EoL) stage. This is necessary in order to assess the environmental impact of materials and processes involved during the whole product or system life cycle. Only then, can impacts be identified and reduction and/or elimination of these implemented. Numerous environmental impact assessment tools have been developed (Wrisberg et al., 2002; Finnveden and Moberg, 2005) in order to assess and identify environmental impacts caused by products/systems. Some of these tools not only allow the assessment of the environmental impact but also provide a decision-making framework to progressively reduce these impacts, this type of tools can be called 'procedural' tools, and there are several types: Environmental Impact Assessment (EIA), Strategic Environmental Assessment (SEA) and Environmental Management Systems (EMS). Other tools are only focused on environmental impact assessment, such as: Life Cycle Assessment (LCA) or Material Flow Analysis (MFA) (Hojer et al., 2008). 'Procedural' tools usually focus on the procedural methods and their relationship with decision-making activities; whereas assessment-only tools focus on technical aspects of the assessment (Wrisberg et al., 2002), such as the assessment of the quantity and quality of input (resources and energy) and output (waste and emissions) involved in the whole life cycle of products and systems. Assessment tools can be used within the framework of a procedural tool (Finnveden and Moberg, 2005). There are also assessment tools that include economic aspects such as: Total Cost Assessment or Accounting (TCA), Cost-Benefit Analysis (CBA), Life Cycle Costing (LCC) and Input-Output analysis (IOA). The latter is also used within the framework of the System of Economic and Environmental Accounts (SEEA). This literature review only considers tools used to assess the environmental impact of products, because these are the ones that can be used and integrated in design processes to aid product developers to assess the environmental impact of the products they design.

This section (2.4.2) is divided in several additional sub-sections which reviews: tools that can assess the environmental of products qualitatively (section 2.4.2.1), tools that can assess the environmental impact of products quantitatively (section 2.4.2.2), and CAD tools with LCA integrated (section 2.4.2.3). The section of tools that can assess the environmental impact of products quantitatively (section 2.4.2.2) is divided into: section 2.4.2.2.1 (LCA tools) which reviews the tools that are based on the LCA method, and their relation with LED-based lighting products (section 2.4.2.2.1.1), and section 2.4.2.2.2 (LCA-based software tools) which reviews the most used software tools based on the LCA method to assess products, and the integration of these in the design process (section 2.4.2.2.2.1).

2.4.2.1 - Qualitative - Environmental impact assessment tools

There are several types of tools that can *qualitatively* assess the environmental impact of products. This type of tool is usually used because they provide a quicker and easier assessment than quantitative environmental impact assessment tools, and although they do not provide accurate (quantitative) results, they can be used during the design process (especially in the early stages) in order to support decision-making processes. They can be classified in two broad categories depending on their format: Matrix-based and polar-based. The main function of these tools is to assess (qualitatively) and compare the products, to select the concept with the lowest environmental impact.

The main problem with these tools, as it will be seen in the next sections, is that in order to fill-in the matrixes and polar diagrams, information has to be input and evaluated by the user. This information and evaluation is very subjective and will vary from user to user depending on their experience and knowledge about environmental assessment and environmental issues.

The main matrix-based tools used to assess the environmental impact of products are: Materials, Energy, Chemical, Other (MECO) matrix (Pommer et al., 2001) shown in fig.2.21, Material, Energy, Toxicity (MET) matrix (Brezet and Van Hemel, 1997) shown in fig. 2.22, Environmentally Responsible Product Assessment (ERPA) (Graedel and Allenby, 2003) shown in fig. 2.23, ABC analysis (Tischner at al., 2000) shown in fig. 2.24-2.26. All these tools are similar, and provide a matrix with different criteria in the X and Y axis that is used to assess the environmental impact of the product. MECO, MET and ERPA basically assess the input/output of each life cycle stage of the product, and the ABC analysis assess the product based on some criteria. The drawback with all these tools is that the information required to fill-in the matrixes cells or to answer the questions asked is not usually available during the design process (especially early stages) and the type of information requires specific expertise about environmental issues in order to be answered. Even in cases where the product has already been designed and manufactured, it is very difficult to obtain the type of data requested. The data input in these cells will be different depending on user experience and knowledge about environmental issues, and hence it cannot be considered objective and reliable when the user is not an expert. The authors of the ERPA tool already warn product developers that the results of this tool are subjective and that a user not familiar with environmental issues can experience challenges to use the tool. To solve this problem, another matrix is provided which shows examples of types of impacts at each product life cycle so the user can understand what type of information have to be filled-in. The tool, however, is still difficult to use because the type of information required is not easy (sometimes impossible) to obtain. In addition to this, if the information is available, the user has to evaluate and assess (score) the environmental impact of that information based on his knowledge and experience, which can create subjective results at best, and totally inaccurate results in the worst case scenario with users who have no experience about environmental impact assessment.

	Material	Manufacture	Use	Disposal	Transport
1. Materials a) quantity b) resource					
2. Energy a) primary b) resource					
3. Chemicals					
4. Others					

Figure 2.21. MECO tool.

		Material cycle Input/ Output	Energy use Input/ Output	Toxic emissions Output
Production and supply of materials and components (suppliers)				
In-house production				
Distribution				
Utilisation	Operating			
	Servicing			
End-of-life system	Recovery			
	Disposal			

Figure 2.22. MET tool.

Life cycle stage	Materials choice	Energy use	Solid residues	Liquid residues	Gaseous residues
Premanufacture	1.1	1.2	1.3	1.4	1.5
Product Manufacture	2.1	2.2	2.3	2.4	2.5
Product Delivery	3.1	3.2	3.3	3.4	3.5
Product Use	4.1	4.2	4.3	4.4	4.5
Refurbishment, Recycling, Disposal	5.1	5.2	5.3	5.4	5.5

Figure 2.23. ERPA tool.

Criteria	A (problematic)	B (medium)	C (harmless)
1. Compliance with environmental regulation	No compliance	There will be stricter regulation than the present compliance allows for in the near future	Compliance is sufficient also for the near future
2. Social requirements	Highly criticised, demands for banning the substance	Criticised, stricter regulation is demanded	No criticism known
3. potential environmental impacts (under normal conditions)			
Toxicity	Hazardous to health: cancerogenicity teratogenicity , genotoxicity, declaration as: • highly toxic, • toxic or • less toxic according to hazardous substances regulations	Hazardous to health Allergenic potential Limit values existing, like TLV (occupational threshold limit value)	According to current knowledge there are no health hazards
Air pollution	Vaporous, gaseous or particulate substances that destroy atmospheric ozone, and criteria of A under 'Toxicity'	Vaporous, gaseous or particulate substances that contribute to smog and dust pollution, and Criteria of B under 'Toxicity'	According to current knowledge no contribution to air pollution
Water pollution	Highly toxic/ toxic to water flora and fauna, according to national regulation	Less toxic to water flora and fauna, according to national regulation At least B, if there is a note on the safety sheet, that the substance must not be released into ground or surface waters	In general not toxic to water flora and fauna,

Figure 2.24. ABC analysis tool.

Criteria	A (problematic)	B (medium)	C (harmless)
4. risk of accidents	High risk of accidents Ranking A, according to national regulation on inflammable substances, or according to regulation on hazardous substances with respect to inflamability: high, medium, danger of explosion: high or medium, danger of explosion at ambient temperatures, Risk of accidents bearing high danger to men and environment Products of combustion toxic according to A under 'Toxicity'	Medium risk of accidents, bearing high danger to men and environment	No risk of accidents , According to current knowledge no special danger apart from the risks otherwise associated with fires
5. raw materials extraction	Raw materials extraction is associated with high environmental impact by emissions Raw materials extraction gives rise to severe disturbance of ecosystems (e.g.deforestation of rain forest)	It is well known that raw materials extraction is associated with environmental impact by emissions. Raw materials extraction gives rise to disturbance of ecosystems	Raw materials extraction is not associated with environmental impact by emissions Sustainable/ renewable resources are used, taking care of sustainable production methods
6. Pre production	It is well known that, during pre-production substances are used as raw materials, ancillary materials or fuels, or substances are emitted which have a high environmental impact	It is well known, that during pre production substances are used as raw materials, ancillary materials or fuels, or substances are emitted which give rise to environmental impacts	Pre-production does not lead to any relevant environmental impacts

Figure 2.25. ABC analysis tool.

7. Manufacturing and Processing	During manufacturing and processing, substances are used or emitted, which are ranked as A under 'toxicity'	During manufacturing and processing substances are used or emitted, which are ranked as B under 'toxicity'	During manufacturing and processing no substances are used or emitted, which give rise to environmental impacts
8. Use phase	Environmental impacts in terms of health hazards which are ranked A under 'toxicity'	Environmental impacts in terms of health hazards which are ranked B under 'toxicity'	According to current knowledge, there are no environmental impacts in terms of health hazards associated with using the product
9. End of Life	Waste treatment leads to environmental impacts	Deposition as municipal waste	No waste deposition, instead reuse, recycling or composting
10. Recyclability	Not recyclable or there is no recycling facility	Partially recyclable, Downcycling (mixed plastics fraction), extremely energy intensive recycling procedure, recycling procedure does not comply to the state of the art	High recyclability according to the state of the art, recycling maintains original technical characteristics (e.g. vacuum moulded steel), or compostability
11 Internal environmental costs (insurance, costs for personnel and investments, fees for waste water or other wastes)	High	Medium	Low or none

Figure 2.26. ABC analysis tool.

The main polar-based tools used to assess the environmental impact of products are:

Sony Polar diagram (Hopfenbeck and Jasch, 1995) shown in fig. 2.27, Spider diagram Econcept (Tischner et al., 2000) shown in fig. 2.28, Eco-compass (Tischner et al., 2000) shown in fig. 2.29, and Eco-lids Wheel (Brezet and Van Hemel, 1997) shown in fig. 2.30. The principles used for the assessment of these are very similar to the ones used in matrix-based tools. The main difference is that in polar-based tools the criteria is displayed in a polar diagram, so the results are easier to visualise and compare visually between products or concepts.

The problem with these tools (like in the case of matrix-based tools) is to provide a score (judgement) for each criteria based on the assessment of the product. This is because the definition of the criteria is such that it is difficult for product designers at the design stage to answer or provide a score based on these criteria. Although the Sony polar diagram (specially), and Econcept, provide criteria which is easier to answer than the matrix-based tools, other polar-based tools such as the spider diagram Eco-compass tool provide general criteria that makes comparison between concepts demanding. For example: it is difficult for the product designer at the design stage to provide values about: health and environmental risks, energy intensity, mass intensity. The author believes the root of the problem is that the majority of these tools and criteria were defined by environmental scientists or LCA experts, for environmental scientists or LCA experts. As well as the language being challenging, the criteria and parameters used are difficult to understand, and the data requested challenging to obtain by a product developer.

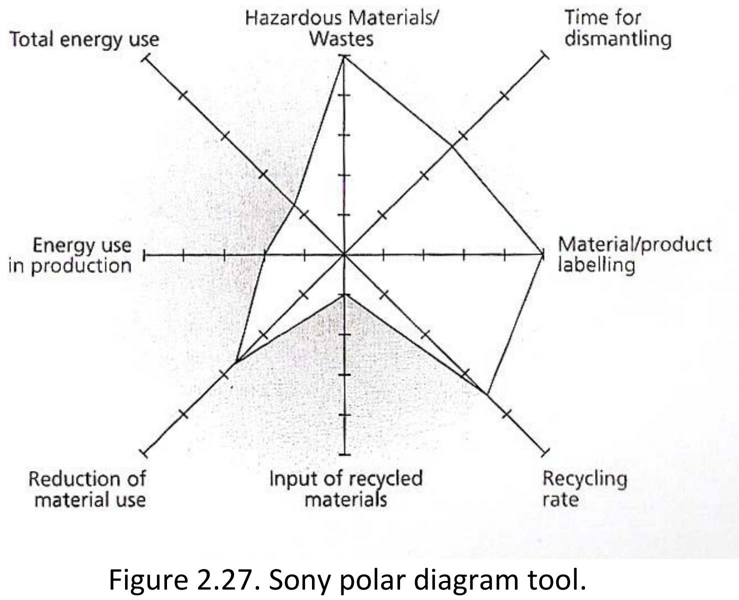


Figure 2.27. Sony polar diagram tool.

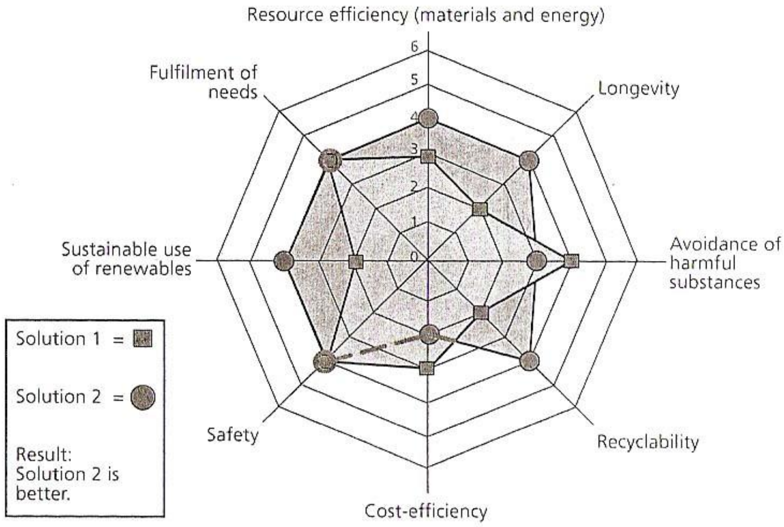


Figure 2.28. Spider diagram Econcept tool.

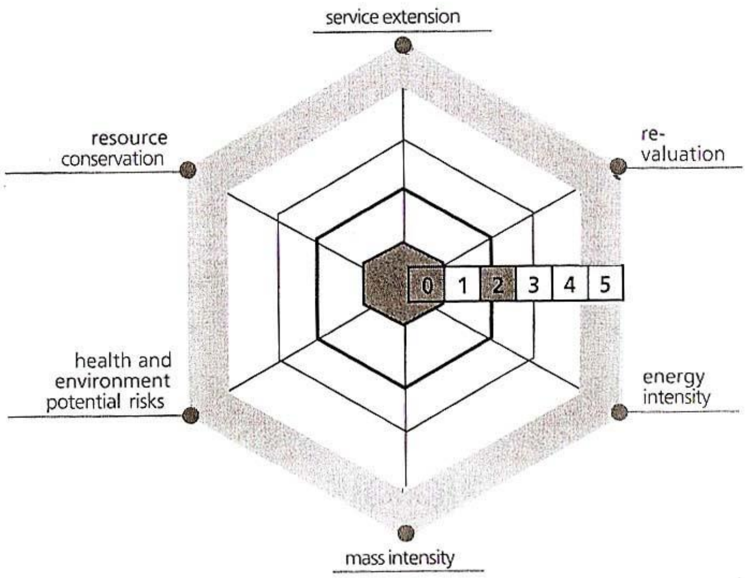


Figure 2.29. Eco compass tool.

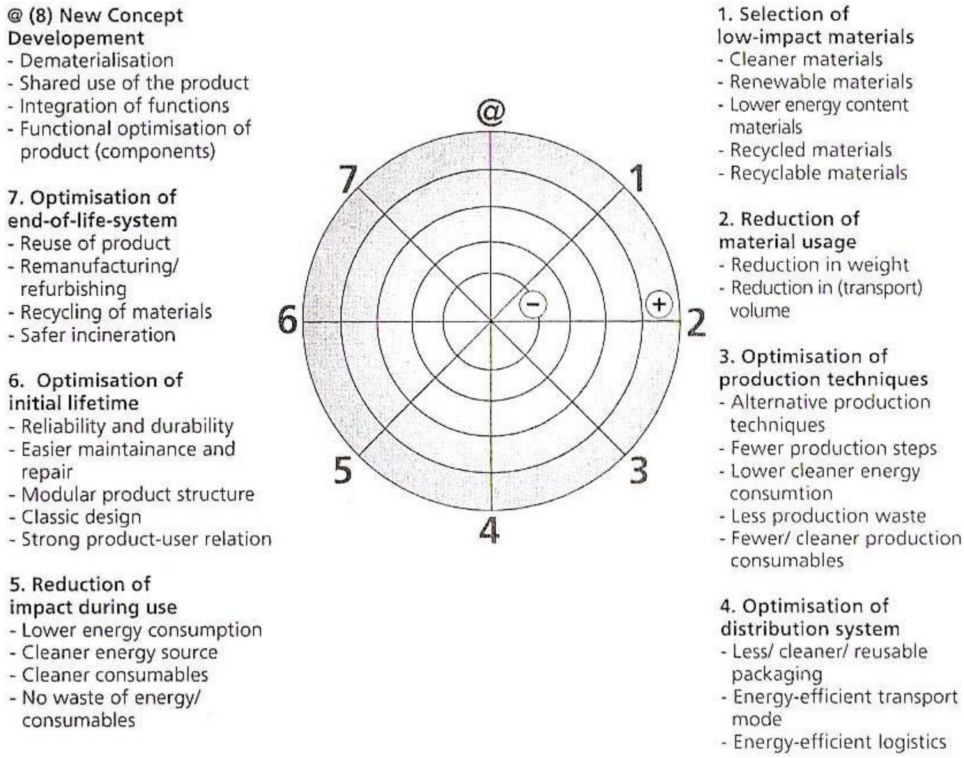


Figure 2.30. Eco-Lids wheel.

2.4.2.2 - Quantitative - Environmental impact assessment tools

There are several types of tools that can *quantitatively* assess the environmental impact of products. These tools are usually based on the LCA method and normally require time and specialised knowledge and skills to apply them. These can be classified in two main categories: LCA-based software tools and CAD tools with LCA integrated.

The main disadvantage with LCA-based software tools is that they are more time consuming and require more expertise to use than qualitative tools such as matrix-based or polar-based tools. However, they provide the most objective, accurate and reliable assessment results when compared with other type of eco-design tools. The reason why these tools are superior in terms of quality of results is because they are based on a well-established and sound methodology (LCA method) and databases.

2.4.2.2.1 - LCA tools

One of the environmental impact assessment tools that can be used to assess (quantitatively) the environmental impact of products is the LCA tool-method. Today, standardisation of LCA methodology has strengthened its status as perhaps the most important tool for assessing a project’s overall environmental impact (Malmqvist, 2004).

LCA, adopts a life cycle approach, and involves the evaluation of all aspects of a product system through all the stages of its life cycle.

However, LCAs are never complete and entirely accurate because there is never access to the fully required set of real data of all the processes and materials involved in a LCA, so all LCAs can be considered 'streamlined' or simplified to some extent. All LCAs omit data and make assumptions, but the degree of these uncertainties may change from assessment to assessment. Sometimes, the omission or simplification (streamlining) of the assessment is purposefully made by reducing the scope of the study, or by reducing data needs through the substitution of surrogates for data that may not be readily available to the practitioner (Hur et al., 2005). In these cases, assessments are simplified because the product designer or LCA expert may not need the full results of the assessment, or may not need very accurate results. For example, when the aim of the assessment is to compare two different products that use different distribution means, the comparison will have to be focused on in the distribution-transport stage, and there is no need to include the manufacturing, use or end of life stages in the assessment. On the other hand, during the early stages of the design process, the product is not defined enough to have access to all real final data, so many assumptions are made, even though these assessments omit a lot of data, these are still useful and can provide guidance about the life cycle stages and components with higher impact during the design process.

LCA can be used for different purposes during the design process. It can be used when the product is finished and manufactured to provide an environmental profile of the product for eco-redesign (where a reference product is needed) or marketing (eco-labels) purposes or to support product developers' decision-making during the design process by identifying the life cycle stages or components with higher impact.

A typical LCA consists of the following main stages: 1) Goal and scope definition, 2) Life Cycle Inventory (LCI) analysis, 3) Life Cycle Impact Assessment (LCIA) and 4) Life Cycle Interpretation (Lewis et al., 2001., Jensen et al., 1997).

The LCA method is usually embedded in software applications called LCA-based software tools. There are different types of LCA-based software tools that can be used for different purposes. The majority of these have been developed to assess generic product systems, but there are also tailored LCA-based software tools that have been customised for specific applications, these are usually company-specific adaptations of generic software, or software packages programmed directly for the needs of the company. These tools usually contain databases with internal data of the company, as well as secondary data to account for background data. Some of these software applications have been simplified to suit non-LCA experts needs, like product developers, and others present more complex and advanced interfaces and features allowing more complex assessment usually required by LCA experts.

The LCA method is not perfect, and the results provided by LCAs cannot completely and accurately assess a product system objectively, so it is important to understand the limitations of this powerful tool, and acknowledge that its purpose is only to provide *guidance* (more or less accurate depending on the completeness and quality of the data input) about the environmental impact assessment of product systems.

When this tool is used in design processes, the type of LCA assessment and LCA-based software tool selected should be a compromise between practicality and completeness. The compromise will depend on the purpose of the assessment and the data available. For important decisions and/or when all the data is available (a finished product) a more extensive assessment will be necessary and possible. However, for less important decisions, or in situations where there is little time, money, or data, more simplified assessments can be used (Brezet and Van Hemel, 1997). Simplification can be achieved by omitting life cycle stages or components in the boundaries of the product system assessment.

2.4.2.2.1.1 - LCA and LED-based lighting products

Despite the growing demand of LED-based lighting products, not many LCA studies of this category of products have been carried out. Within the limited number of existing studies, some of them assessed and compared LED-based lighting products for street and general lighting applications with non-LED-based lighting products, which used different light source technologies, such as Compact Fluorescent Light, in order to know which one had less environmental impact and where (in which life cycle stage) this impact was allocated

(Principi and Fioretti, 2014; Hadi et al., 2013; Dale et al., 2011, UNETO-VNI, 2011; US DoE, 2012; Tähkämö and Halonen, 2015). Tähkämö et al. (2013) assessed one single LED-based lighting product for general lighting applications, and UNETO-VNI (2011) conducted a comparative LCA of eight LED modules-systems, using the same lighting product housing, 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 scenarios assumed.

The existing studies used different LCIA methods, such as ECO-I-99 (Goedkoop and Spriensma, 2001), TRACI (Bare et al., 2003), ReCiPe (Goedkoop et al., 2013) and ILCD 2011 (EC, 2011). The results were shown using different damage and impact categories. The scope of these studies usually comprised a complete cradle to grave assessment, except a few studies where some life cycle stages, such as end of Life (UNETO-VNI, 2011), distribution (Dale et al., 2011; UNETO-VNI, 2011) and packaging (UNETO-VNI, 2011) were excluded.

Scenarios were assumed in some of these studies. Tähkämö et al. (2013) assumed scenarios based on two different lighting products' useful lives (36,000 h and 15,000 h) and two different electricity mixes (French and European mixes). Principi and Fioretti (2014) assumed scenarios based on two electricity mixes (European and Italian electricity mixes), and three end of lives (Complete recycling, full disposal in landfill, disposal in incinerator). Dale et al. (2011) assumed scenarios based on three different electricity mixes (US average mix, regional mix, and 100% wind power). Hadi et al. (2013) assumed two scenarios based on different electricity mixes (Photo Voltaic panels and solar power plant), and Tähkämö and Halonen (2015) assumed two scenarios based on two electricity mixes (European mix and Hydropower in: Norwegian), two different data sources for LED modelling (US DoE and Ecoinvent), and 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 (Principi and Fioretti, 2014; Hadi et al., 2013; Dale et al., 2011; Tähkämö and Halonen, 2015; Tähkämö et al., 2013): lm (luminous flux), cd/m2 (luminance) and lux (illuminance) produced by the lighting product. Luminous flux measures the perceived power of light, 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 (lighting product function) from the source. Tähkämö et al. (2013) selected a functional unit, which is the luminous flux (lm) produced by the lighting product 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 (Principi and Fioretti, 2014; and UNETO-VNI, 2011). However, the consideration of these light measures are not the most suitable to define the functional unit, because they do not describe the core function of the lighting product, which is to produce a specific quantity of light with a specific quality for a period of time. This is defined clearly by the luminous flux (quantity) and the Color Rendering Index (CRI) and Correlated Color Temperature (CCT) (quality).

The period of time considered in the functional unit should correspond to the useful life of the lighting product.

To date, there are a few studies that assess LED-based lighting products and, in some cases, compare them with non-LED lighting products, but there are none that assess and compare them with other LED-based lighting products. In addition, researchers (Tähkämö et al., 2013) working in this area has suggested the need to conduct further studies about LCA of LED-based lighting products. This thesis (Chapter 5: Method to assess and compare LED-based lighting products) endeavours to cover this gap of knowledge by defining and explaining the most suitable method to assess and compare the environmental impact of LED-based lighting products, building on the previous studies mentioned in this section. This method has been integrated in the approach to eco-design LED-based lighting products explained in chapter 7.

2.4.2.2.2 - LCA-based software tools

This section will focus on LCA-based software tools. There are many LCA-based software tools available in the market. They differ in their user interface, databases embedded, LCIA methods utilised, results display options, usability, complexity of assessment, and advanced features offered. Some of them present similar specifications but are manufactured by different suppliers. *The most relevant* LCA-based software tools used to model the environmental impact of products are the following: Simapro (PRé Consultants, 2015), Gabi (Thinkstep, 2015) and Sustainable Minds (Sustainable Minds, 2015). Simapro and Gabi allow to carry out detailed modelling and assessment of the environmental impact of any general product system (product, process or activity) produced in nearly any part of the world (the databases have worldwide coverage); and also allows to conduct complex end of life scenarios. Sustainable Minds is less advanced than Simapro and Gabi and does not allow the conduction of multifaceted and detailed assessments with complex end of life scenarios. Sustainable Minds can import Bill of Materials (BoM) from CAD software. Other key feature is the possibility to compare-assess different concept designs easily.

Simapro and Gabi have up-to-date databases and Life Cycle Impact Assessment (LCIA) methods, and are available in several languages and versions.

2.4.2.2.2.1 - Integration of LCA-based software tools in design processes

The rapid growth of LCA-based software tools has resulted in a wide variety of LCA-based software options available for different purposes. For example, some of these have been designed to be used by non-experts and allow quick (screening) assessments, whilst others allow more detailed assessments that require more expertise and time. Furthermore, some of these tools have been developed to assess specific categories of products (i.e. packaging), which makes them very efficient and suitable for users working in a specific area.

There are mainly two types of LCA-based software tools based on their purpose: *Screening and detailed*. *Screening* tools are usually used to conduct less detailed (Screening) environmental impact assessments. The results of the assessment using this type of tools are usually less accurate and detailed than detailed LCA-based software tools. The main purpose of these tools is to conduct a fast 'screening' of the product in order to find the life cycle stages and components with higher impact at the early stages of the design process. They also can be used to guide decision-making processes of product designers when deciding which material, industrial process or design solution to select, especially during the early stages of the design process.

Since the assessment using screening tools takes less time and requires less expertise, these can also be especially suitable when there are time and/or budget constraints which do not allow the use of a detailed LCA-based software tool.

These tools have been designed to simplify the assessment by reducing the amount and accuracy of the data to be input and by lessening data needs through the substitution of surrogates (generic databases for estimated impact of processes and materials) for data that may not be readily available to the designer at the design stage (Hur, T. et al., 2005).

Detailed tools can carry out detailed and accurate environmental impact assessments. These tools can also reduce the time and complexity of the assessment by reducing the scope of the assessment boundaries. The interface is usually less user-friendly (for non-LCA experts), and therefore more difficult and time consuming to understand and use.

These tools are used to carry out detailed life cycle assessments of the product, when there are no resources constraints (i.e. time, budget, expertise, etc.) and accurate results are required. These usually allow the use of a large number of databases and environmental impact assessment methods in the assessment, and to create, import and export databases of new materials and processes. Since these tools have been developed for LCA experts, they usually present advanced analysis options, like sensitivity analysis or the possibility to create complex end of life scenarios, and results can be shown at a substance level, which is usually required by LCA experts.

In general, ‘Screening’ and ‘Detailed’ LCA-based software tools are used at typical stages during the design process (Casamayor and Su, 2011b). Fig. 2.31 shows when each type of tool (Screening: S and Detailed: D) is usually used.

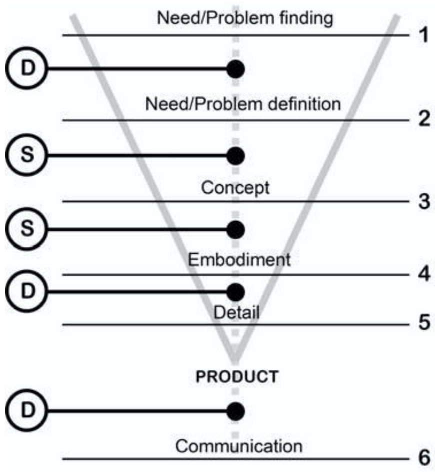


Figure 2.31. Integration of LCA-based software tools in the design process

Fig. 2.31 shows how Detailed LCA-based software tools (D) are used at stage 2 (need/problem definition) to assess the environmental impact of the reference product (when there is a reference product to begin with). This type of tool is used because the quantity and quality of data required for this type of assessment is available at this stage when the reference product has been manufactured, sold and used already. The information obtained from this assessment is used to inform the Product Design Specifications (PDS) of the new product. At stage 3 (Concept design), Screening LCA-based software tools (S) are used. At this stage the product is beginning to be defined, and rapid incomplete assessments and 'what if scenarios' have to be conducted to select the design features of the concept. The assessments at this stage are based on incomplete data and assumptions, and although not accurate, they provide broad guidelines about the impact of design decisions and can identify 'hot spots' of the concepts being developed. At stage 4 (embodiment), the product is more defined and there is more (and more accurate) data to inform the assessment, however there are still areas of the product which need further refinement. Additionally, some information about the product life cycle still unknown so screening tools are used. At stage 5 (detail), the product is more defined and there is enough data to carry out the first comprehensive detailed assessment (D) with detailed tools. Due to the lack of data from the use, distribution and end of life phases, the assessment can be done only from extraction of materials until the product leave the manufacturing facilities (Cradle to gate). Alternatively, a 'cradle to cradle' assessment can be conducted based on assumptions of the distribution, use and end of life stages, since there is no factual data about these stages yet. At stage 6 (communication), the product is already defined, manufactured and first units tested and sold, thus factual data about all stages is available. The results of this assessment (with detail tools) can be used to compare the final total environmental impact of the product developed with the reference product, in order to know if the environmental impact has been reduced and in which stage/s. It can also be used for internal use of the company, to inform ecolabels, suppliers or Environmental Product Declarations (EPD).

The features of Detailed and Screening LCA-based software tools used based on specific criteria (Input, Output, User and Assessment) are explained in table 2.3.

	Detailed tools	**Screening tools**
Input	High amounts of detailed factual data are needed	Low amounts of basic estimated data are needed
Output	Accurate/objective detailed results communicated with a wide range of indicators	Estimated/subjective basic results communicated in a limited number of indicators
User	More knowledge and time is required. Suitable for LCA experts.	Less Knowledge and time is required. Suitable for non-LCA experts
Assessment	More impact assessment methodologies and databases available. Not very suitable to create 'what if scenarios' used in design processes	Less impact assessment methodologies and databases available. Suitable to create 'what if scenarios' used in design processes

Table 2.3: Advantages and disadvantages of LCA-based software tools

The features of both types of tools shown in table 2.3 are described below in more detail:

<u>Input data required for the assessment:</u>

Detailed LCA-based software tools require higher amounts of data, and more detailed than Screening LCA-based software tools, and screening tools require less data and much of this is based on estimates, not on real factual data. Usually screening tools provide databases with materials, industrial processes, and sometimes parts/components which makes easier the assessment for non-LCA experts.

Output data required for the assessment:

The output of detailed LCA-based software tools is more detailed and accurate than the results produced with screening tools, this is so because the amount of data input is higher and more comprehensive, usually based of factual real (not estimated) data, and also because the impact assessment methodologies used are more complex and rigorous. Detailed tools can show results based on several types of indicators, but usually the results need interpretation by users with knowledge about LCA and/or environmental impact in order to be meaningful for product designers.

User:

The interface of detailed LCA-based software tools is usually more complex, which reflects the fine detail of data that can be input for assessment, as well as the higher number of advanced functionalities that can be used to conduct the assessment. Detailed tools also allow higher level of transparency about the assessment process conducted by the software, and can be customised, which is a feature appreciated by LCA experts. However, for product designers this type of tools can be time-consuming, not flexible, and too demanding in terms of data quantity and quality required. In addition, many of the advanced features, useful for experts, are usually not used by product designers because this level of detail of assessment is not required for their needs.

Assessment:

The assessment itself depends on the functional features provided by the software to carry out the assessment. Detailed LCA-based software tools allow selection of a higher number of impact assessment methodologies and databases to support the assessment. It also allows displaying the results with a higher number of environmental indicators. One of the main differences and advantages of LCA-based screening software tools is that they are suitable to create 'what if' scenarios, which are very common (and useful) in eco-design processes. For instance, product designers can constantly check what environmental impact the product would have if a new material, industrial process or part was selected. These tools usually allow changing the parameters of the assessment quickly to see the results and compare them with other options to support decision-making.

2.4.2.3 - CAD tools with LCA integrated

CAD tools with LCA integrated are CAD tools that incorporate functionalities from LCA-based software tools. The advantages of this category of tools are: 1) Once the product has been modelled in the CAD tools (a typical activity in design processes) all the product data (i.e. BoM) is available in real-time to be input in the LCA assessment, which can be done simultaneously and quickly, 2) The other key advantage is that, the environmental impact resulting from design changes (i.e. change of geometry, or material) can be seen in real-time, so 'what if' scenarios are easy and fast to model.
Since the products modelled in the CAD tool are defined in detail (which is necessary to model them in CAD), the input data for the LCA is comprehensive.

Solidworks-Sustainability (Dessault Systemes, 2015) is one of the CAD tools with LCA integrated available. It provides LCA functionality in a CAD software application. It can be considered a 'screening' type of tool, although the databases and environmental impact assessment methods used are provided by Gabi (detailed LCA-based software tool). It can provide real-time assessment of the products modelled in Solidworks. The results are shown based on four environmental indicators: Air acidification, carbon footprint, total energy consumed and water eutrophication.

One of the disadvantages of this tool is that product designers need to model the product in Solidworks, which means that product designers that use other CAD software cannot use it. Another disadvantage is that this tool does not allow a complete detailed LCA, and the amount of functionalities and assessment possibilities that are possible with LCA-based software based tools such as Simapro or Gabi are not possible.

2.4.3 - Databases

Databases are the core tools for the environmental impact assessment of products. The quantity and quality of the data contained in databases will determine the quality and accuracy of the results of the assessment. Databases are the key element of LCA-based software tools and are embedded in these tools to make the assessment possible.

Databases contain datasets of Life Cycle Inventory (LCI) of numerous materials, manufacturing processes and other industrial processes such as transport, or waste treatment processes from different countries worldwide.

There are many databases which have been created by professional associations, private companies and research projects. Some of the most well-known databases, described in more detail in Appendix 2.1, are listed below:

- Hazardous Substances Data Bank (HSDB) (U.S. National Library of Medicine, 2015).
- European Aluminium Association database (European Aluminium, 2015).
- European Federation of Corrugated Board Manufacturers (FEFCO) (FEFCO, 2015).
- International Iron and Steel Institute (IISI) (IISI, 2015).
- The EcoInvent database (Ecoinvent, 2015).
- CPM LCA Database (Swedish lifecycle centre, 2015).
- EIME (Bureau Veritas CODDE, 2015).
- Esu-services databases (ESU-services, 2015).
- Eurofer data sets (Eurofer, 2015).
- Global Emission Model for Integrated Systems (GEMIS) (IINAS, 2015).
- IVAM LCA Database (IVAM UvA BV, 2015).
- Plastics Europe Eco-profiles database (PlasticsEurope, 2015).
- The Boustead Model (Boustead Consulting, 2015).
- US Life Cycle Inventory (USLCI) Database (NREL, 2015).

Up to date accurate data of the input (energy, and resources) and output (waste and emissions) of industrial processes used to manufacture, use, distribute and dispose products is key to assess the environmental impact of products. One of the problems product designers have is that the data they need to assess their products is not available or it may take too much time to retrieve. The databases role is to provide LCI datasets easily to facilitate environmental impact assessments. However, the data from the databases, which has been obtained by industrial associations and research projects, sometimes do not match exactly the data needs of the product designer or LCA expert. In these cases, similar data (surrogates) from the databases have to be used instead of the exact data needed. This means that the results of the assessment are not fully accurate, but still are accurate enough to provide approximate results that can guide eco-design processes. That is why a Life Cycle Assessment (LCA) is never entirely complete and accurate, because it is nearly impossible to obtain the complete real input/output data of each industrial process involved in the product life cycle. Usually, the data needed is not fully available or it may take too much time, so the majority of the environmental impact assessments are based on data obtained from databases, instead of by the data collection of the actual processes and materials involved in each product life cycle.

The improvement of the field of environmental impact assessment of products is strongly influenced by the quantity and quality of the databases available. That is why more research focused on the collection of data from more industrial processes from different geographical areas is needed in order to improve the accuracy and reliability of the environmental impact results of the products conducted by product designers. Another area of key importance is the study of the environmental Life Cycle Impact Assessment (LCIA) methods used to assess this data.

2.4.4 - Tools to improve the reliability of the product

There are different types of tools that can improve the reliability (and hence durability and lifespan) of a lighting product. Standards and certifications can ensure that the lighting product (and its electrical-electronic components) will provide its function for a period of time under certain operating conditions specified in the standards and certifications. Software-based simulation tools allow to the virtual simulation of how the lighting product will function under specific operating conditions during the design stage before physical prototypes are made. The use of this type of tools early on can improve the reliability of the lighting product, as well as save time and money during the design process. Design changes can be carried out early on informed by simulations results, instead of later on when design changes are more expensive and difficult to implement.

Tests and testing methods are also usually used to pass standards and obtain certifications. The type of test and testing method to be used is specified by each standard.

Standards and certifications:

Standards are established norms or requirements in regard to technical systems. Usually, these are formal documents establishing uniform engineering or technical criteria, methods, processes and practices. These are usually used as criteria to verify product performance requirements when products are tested.

Compulsory and voluntary certifications ensure minimum quality and reliability requirements in products. For example: the CE certification is compulsory in products that are going to be commercialised in EU, and products have to pass specific tests in order to achieve this certification. Some of the tests undertaken to obtain these certifications increase the reliability, safety and the lifespan of the lighting product, and others require minimum performance outputs in terms of energy (e.g. Energy Star label).

Appendix 2.2 shows the standards applied to the lighting product developed, which comprises standards for: LED-based lighting products and modules, LED - control gear and LED components.

Software-based simulation tools:

These tools are used to simulate the functioning of the lighting product under specific operating conditions in a computer. Basically, these tools can model the behaviour of lighting products in specific conditions, to demonstrate how they will behave in real-world or extreme operating conditions. This type of tool can help reduce the material used in the lighting product or increase their reliability. These tools are usually complemented with physical tests of the lighting product in the last phase of the design process.

- Solidworks – Simulation (Dassault Systemes, 2015a): Is a tool to model and simulate the functioning of products under specific operating conditions. This tool allows the functioning product to be simulated under specific forces, pressures, accelerations, temperatures and contacts between components.

- ANSYS (Ansys, 2015): Is a tool used to conduct virtual simulations of systems and products.

- Gabi DfX (ThinkStep, 2015): Is a tool used to simulate and analyse the end of life of products. It provides functionalities to support Design for Disassembly (DfD), Design for compliance (DfC) and Design for Recycling (DfR).

<u>Tests and testing methods:</u>

Tests are used to confirm the lighting product will function properly under certain conditions for a period of time. Tests are like real-life simulations, and the aim is to ensure certain level of reliability of the lighting product. Lighting products that have passed certain standard tests receive a certification, which communicates the consumer that the lighting product has satisfied certain quality requirements. Tests can reduce the risk of future failure of the product, hence increasing its lifespan. Lighting products that do not pass the tests need to be re-designed before manufacturing begins. Some of these tests are required for basic compulsory certification in some markets (like the CE marking), and others are voluntary (i.e. high-quality certifications), and are conducted to increase the quality of the lighting product. Typical tests carried out in eco-lighting products are:

- CE tests: Tests used to assess the reliability and safety of the lighting product and its components in order to obtain the CE certification.
- Ingress Protection (IP) tests: Tests used to evaluate the sealing properties of the lighting product in order to pass the IP certification.
- Light sources tests: Tests used to assess the light sources performance over time (lifespan).
- Disassembly tests: Tests used to assess the disassembly potential of the lighting product.
- Light tests: Tests used to analyse the light output (quantity and quality) of the lighting product.
- Power consumption tests: Tests used to measure the energy consumption of the lighting product.
- Thermal tests: Tests used to analyse the thermal behaviour of the lighting product.

2.4.5 - Tools to communicate the environmental profile of the product

These type of tools are used to communicate the environmental credentials of the lighting product to the consumer. The most well-known are Eco-labels and Environmental Product Declarations (EPD).

<u>Eco-labels:</u>

Products that have been certified with an eco-label inform the customer that the product has passed specific environmental standards. Currently (2016) there is no eco-label for lighting products, but research (Ecolighting, 2015) is being carried out to develop an eco-label for lighting products.

The 'Energy Star' label (EPA, 2015) is available for lighting products only in the US at the moment. In the EU, this label can be applied to other type of energy-using products but not to lighting products. This Eco-label set specific requirements for lighting products in terms of energy consumption, light output quality, and lifespan. For example, it specifies minimum energy-efficiency ratios for lighting products, proper light distribution, longer lifespans, longer warranties and the implementation of energy-saving strategies such as the use and integration of dimmers and sensors.

<u>Environmental Product Declarations:</u>

Another option to inform the customers about the environmental credentials of a lighting product, and probably the only one at this moment, is through Environmental Product Declarations (EPD) (EPD International AB, 2015), which is an independently verified document that communicates the environmental profile of a product based on LCA results.

2.4.6 - Tools to select materials, components and processes

This group of tools support the selection of materials, manufacturing processes and components with low environmental impact. The most useful and well-known tools are the CES Selector (Granta Design, 2015) and the Eco-Indicator 95/99 (Goedkoop and Spriensma, 2001). CES Selector provides information about different properties (i.e. mechanical, thermal) of each material including the environmental impact. It is a suitable tool to compare and select materials and manufacturing processes. It also can perform basic environmental impact assessment of products, although these assessments are not very comprehensive. Eco-Indicator 95/99 provides a list with the environmental impact (based on scores) of the most common materials and industrial processes, based on the Eco-indicator 95/99 methodology. Eco-Indicator 95 provides 100 eco-indicators of the most common materials and processes; and Eco-Indicator 99, the later version, provides over 200 eco-indicators. One of the problems of this tool is that it is out of date. Although it was initially used to guide materials and manufacturing process selection by product designers when there were no better tools to fulfil this need, today this need can be fulfilled with LCA-based software tools, or other materials selection tools such as CES Selector (Granta Design, 2015) which have databases and assessment methods that are continuously updated.

LCA-based software tools:

LCA-based software tools such as Simapro (Pre Consultants, 2015b), Gabi (Thinkstep, 2015) and Sustainable Minds (Sustainable Minds, 2015) have embedded high-quality up to date worldwide databases that can support material, manufacturing processes and components selection during the design process. Although some of these (i.e. Simapro and Gabi) are complex and specialised tools developed for LCA, they can also be used to support materials, manufacturing processes and components selection if the product designer has the knowledge and skills to use them. There are other LCA-based software tools which are easier to use like Sustainable Minds, which although it has less quantity and quality of databases and less impact assessment methods, can also provide basic guidance to support decision-making processes.

LED driver selector on-line web-based application (Future Lighting Solutions Inc, 2015):

The driver selector tool helps choose the optimum driver model for a specific LED model. Once the brand and type of components (LEDs and driver) are selected, the specific model of each type of component (LED and LED-driver) is selected, based on the results of this tool to optimise the energy efficacy of the LED-LED driver system.

Thermal resistance datasheets:

Thermal resistance datasheets from suppliers are used to guide heat sink design. The aim of this tool is to optimise-minimise the use of material in the heat sink as much as possible for a given function. Sometimes, heat sinks size and fins are over dimensioned, thus wasting material, because it is not understood how thermal resistance works in heat sinks.

2.5 - Summary of literature review

The literature review has covered the eco-design process models and methods, the eco-design tools, regulations and directives, and the studies related with design of eco-lighting products and the types of lighting products, services and systems. All the methods and tools reviewed are used to reduce the environmental impact of generic products, and generally adopt a life cycle approach, which takes into account all the life cycle stages of the product life cycle (manufacturing, distribution, use and end of life). Eco-design tools were also reviewed to analyse the advantages and disadvantages of these. Different types of eco-design tools for different purposes were reviewed. Some of them were ‘prescriptive’ such as guidelines, and checklists. Others were ‘analytical’, and were used to allow the qualitatively (matrix and polar-based tools), and quantitatively (LCA-based software tools) environmental impact assessment of products. There are two main types of LCA-based software tools according to the type of assessment results they provide: Screening and Detailed LCA-based software tools. The integration of each type within the design process has been reviewed and discussed. It has been concluded that, in general, detailed LCA-based software tools are more suitable for the beginning and the end of the design process, and screening LCA-based software tools are more suitable for the middle stages of the design process. The integration of LCA functionalities into CAD tools has also been reviewed, and how this integration makes the application of LCA much easier for product designers, allowing the seamless combination of environmental impact assessment in real-time during the design process. Databases, which are a key aspect of the LCA tool-method have also been reviewed. The correlation of the quantity/quality of the data with the quality of the LCA assessment results has also been explained. Other tools that may contribute to reduce (indirectly) the environmental impact of lighting products have also been discussed: Tools such as standards or certifications can improve the reliability and durability of the lighting product, contributing to extend its lifespan, and software-based simulation tools and tests can simulate and physically analyse the lighting products. Tools that contribute to communicate the environmental credentials of the product to the consumer have also been reviewed, and the main tools available are eco-labels (not available for lighting products yet), the energy star label (not available for lighting products in EU), and the Environmental Product Declarations (EPD). All of these 'labels' usually require LCA reports of the lighting product in order to be certified.

Through this review the need to study the eco-design process of LED-based lighting products has been identified. This will increase the understanding of it, and inform a descriptive model and a specific approach or method to eco-design LED-based lighting products. Although some of the features of existing models, methods and approaches to design generic products are also applicable to LED-based lighting products, the eco-design of this category of products present particular characteristics that require specific approaches, which highlight the need for this research.

Chapter 3: Methodology

This chapter explains the methodological approach followed in this research. It begins by outlining the key elements of this approach (section 3.1): Epistemology, theoretical perspective, research approach, research methodology, timeframe and data collection methods. Next, it describes the research methodology and data collection methods used in more detail (sections 3.1.1 and 3.1.2).

3.1 - Methodological approach

In order to achieve the aim and objectives of this research, a combination of two research methodologies have been utilised: *Case study research* (section 3.1.1) and *survey* (section 3.1.2). Case study research has been used to describe, examine and analyse a real-world single-case based on the process followed to design a LED-based lighting product with low environmental impact, undertaken by the author with a lighting manufacturer (Ona Product S.L.) over a period of three years. In addition to the case study, a survey to study the lifespan of LED-based lighting products and the causes of their end of life has also been utilized, in order to inform design guidelines that could be applied during eco-design processes to extend the useful life of LED-based lighting products.

Fig. 3.1 shows the methodological approach followed, with its key elements: Epistemology, theoretical perspective, research approach, research methodology, timeframe and data collection methods.

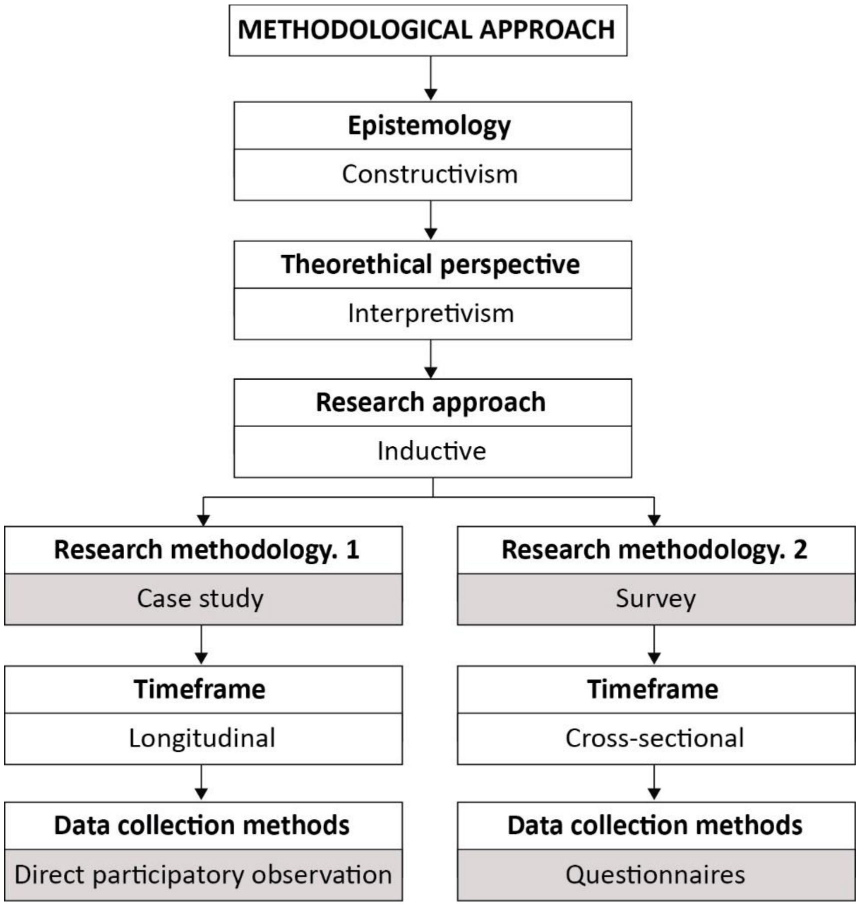


Figure 3.1. Methodological approach.

The research methodologies selected (case study and survey) were underpinned by specific epistemologies and theoretical perspectives views, as well as particular research approaches and timeframes determined by the data collection methods chosen.

Epistemology:

This research has been conducted and underpinned by a constructivist epistemological perspective. Constructivists hold the view that the manner to understand about the world is not independent from the researcher, but that knowledge is created (constructed) by the researchers' interactions with the world (Gray, 2009). On the other hand, objectivists believe that knowledge and understanding of the world exist independently of researchers' consciousness. In this sense, for objectivists, the world phenomena can be understood and discovered objectively.

Theoretical perspective:

This research has adopted an interpretivist theoretical perspective. The interpretivist perspective holds the view that the social world is fundamentally different from that of the natural and physical world, and that the understanding of this requires a different logic of research procedure, one that can grasp the subjective meaning of the social phenomena (Bryman, 2012). Thus, interpretivists ‘construct’ their own understanding of the world in different ways in relation to the same world phenomenon (Gray, 2009). On the other hand, positivists aim to understand the world objectively based on empirical experimental research through hypothesis testing.

‘Positivism’ is a theoretical perspective more suitable to understand the natural and physical phenomena that takes place in the natural and physical world, whilst ‘interpretivism’ is usually more suitable to understand social phenomena of the social world.

Crotty (1998) explains the need for different theoretical perspectives to understand the physical and natural and social worlds as follows:

“Our interest in the social world tends to focus on exactly those aspects that are unique, individual and qualitative. Whereas our interest in the natural world focuses on more abstract phenomena, that is, those exhibiting quantifiable, empirical regularities”.

Research approach:

The interpretivist theoretical perspective usually follows an inductive research approach. The inductive approach is grounded on the premise that theories are built based on the data collected from a given phenomenon, so theory is the outcome of the research. The process of induction involves the obtention of ‘generalisable’ inferences out of observation (Bryman, 2012). Positivists, on the other hand, believe that the only way to understand the world is by adopting a deductive research approach, where hypothesis are proposed, and then confirmed or rejected through empirical experimental research. This research has followed an inductive research approach based on the data collection and analysis of a contemporary event (process) in order to build a ‘theory’ (approach) regarding the case study research.

Surveys can follow an inductive or deductive approach depending on the type of survey conducted. Descriptive surveys tend to follow an inductive approach, whilst analytical surveys tend to follow a deductive approach (Gray, 2009). The descriptive survey used in this research follows an inductive approach because there was no initial research question or hypothesis that had to be confirmed or rejected with the results of the survey.

Research methodology:

The research methodology used in this research is *case study research* and *survey*. Case study research is a suitable methodology to describe, examine and explain a ‘case’, based on a contemporary real-world event (such as a process) over time. It is very adequate for the study of events where there is no control over the (behavioural) parameters of the event, and the aim is to research ‘how’ questions (Yin, 2014).

Although case study research is especially suitable to study ‘particular’ cases, it can also be used to study a ‘common’ case such as an industrial everyday process. It can be based on multiple-case studies or a single-case study; the present research case study has been based on a single case study.

One of the main problems with case study is that it has been claimed that the results from a single case study are difficult to generalise. However, Yin (2014) states that, as it is done in science research with experiments, several case studies (like experiments) can be conducted on the same topic in order to ‘generalise’ the findings. Other exponents of case study research argue that the purpose of this research methodology is not to generalise to other cases. They tend to argue that the aim is to generate an intensive examination of a single case, in relation to which they then engage in theoretical analysis (Bryman, 2012).

Schramm (1971) defines the case study research as follows:

“The essence of a case study, the central tendency among all types of case study, is that it tries to illuminate a decision or set of decisions: Why they were taken, how they were implemented, and with what result”.

A survey has also been used as an additional research methodology to find out what was the lifespan of LED-based lighting products, and what the causes of their end of life were. This information can inform LCA (lifespan of LED-based lighting products), and eco-design guidelines to extend the lifespan of LED-based lighting products.

Data collection methods:

The data collection method used to gather data during the case study research was *direct participatory observation*.

The data collection method used to gather data during the survey research was on-line self-completion close-ended *questionnaires*.

3.1.1 - Case study

Case study research methodology was selected to describe and examine a real-world single-case based on the process followed to design a LED-based lighting product with low environmental impact.

Other similar research methodologies that follow the same theoretical perspective, such as action research and grounded theory, were not selected for the following reasons:

Although *Action research* may also be selected to explore a process from the point of view of the practitioner who may be involved using direct participatory observation, the key feature of this research methodology is that the aim of the study has to be to improve an organisation or process for example. The aim of this research was not to improve, implement and test the process followed in this case study, but to describe and examine it to understand it better and be able to model it, and based on that descriptive model, propose an approach to eco-design LED-based lighting product that could be used by Product developers in the future.

Grounded theory is also an inductive approach which seeks to obtain or 'ground' a theory, based on data collection from the field. However, it is not advisable when there is no pre-existing theoretical ideas and assumptions about the topic to be explored (Robson and McCartan, 2011). The present research began with no pre-existing ideas or topics to be researched, since the aim was to 'elicit' or find unexpected insights of a real-world contemporary event from the point of view of a practitioner (product designer).

The case study research used had the following characteristics:

- *The case study question:* How to reduce the environmental impact of LED-based lighting products during the design process.
- *The study propositions are to explore:*

1. Key product-related features that affect the environmental impact of LED-based lighting products.

2. Eco-design tools, techniques and methods used at different stages during the design process to reduce the environmental impact of the LED-based lighting product.

3. Advantages and disadvantages of each of the tools, techniques and methods used.

4. Method used to assess and compare the environmental impact of LED-based lighting products.

- *Unit of analysis:* The <u>process</u> followed to design a LED-based lighting product of low environmental impact.
- *Type of event:* The event was based on a contemporary real-world design process followed by a product designer with a lighting manufacturer.
- *Timeframe/duration of event:* Longitudinal study: 3 years
- *Data collection method:* Direct participatory observation

The data collection method used during the case study was direct participatory observation. The researcher (author) played an active-covert role during the study, observing and participating (active) in the process, as a product designer, without informing about his research activities (covert). This allowed him to describe, examine and study the process in-depth, and experience first-hand the advantages and disadvantages of methods, tools and techniques used during the eco-design process, as well as the problems of implementing these in real-world situations where lighting manufacturers wish to design and develop LED-based lighting products with low environmental impact.

3.1.2 - Survey

A survey was selected as a research method to study the lifespan of LED-based lighting products and the causes of their end of life, in order to inform LCA (e.g. lifespan of LED-based lighting products), and design guidelines that can be applied during eco-design processes to extend the useful life of LED-based lighting products.

'Descriptive-analytical survey' was the only research method available to obtain the type of information required for this study, because this is the only research method that could capture and analyse data from consumers and manufacturers past and present events.

There are several possible data collection methods that can be used to gather the data needed in the survey. Survey data can be collected with: structured-interviews or questionnaires. Structured-interviews can be conducted by telephone or face-to-face, and questionnaires can be distributed by post or by e-mail/website (on-line). This survey utilised questionnaires which were distributed via e-mail, to save cost and speed response time (Robson and McCartan, 2011). One of the disadvantages of this data collection method is that usually obtain low response rates (Robson and McCartan, 2011).

Several types of questionnaires can be used to collect the data, depending on: 1) the type of questions included (e.g. open or close-ended), and 2) if the questionnaire has to be completed by the participant (e.g. self-completion) or another person (e.g. the researcher). This survey used self-completion questionnaires with close-ended questions because the method of distribution chosen only allowed this use. The questions were close-ended because are easier to answer (which is especially important in self-completion questionnaires), and to analyse. It is recommended to avoid the use of open-ended questions as much as possible in questionnaires (Robson and McCartan, 2011; Bryman, 2012).

The survey used had the following characteristics:

- *Data collection method:* Questionnaires (2 types: one for consumers of LED-based lighting products, and another for LED-based lighting product manufacturers).
- *Type of questionnaire :* Self-completion questionnaire with close-ended questions
- *Distribution method:* On-line (via e-mail)
- *Sample:* 1,691 people: 396 manufacturers of LED-based lighting products, and 1295 consumers of LED-based lighting products.
- *Timeframe/duration of the event:* Cross-sectional study/at a single point in time
- *Coverage:* Belgium, Germany, Spain, UK
- *Type of survey:* Descriptive

<u>Questionnaires:</u>

The survey consisted of the distribution of two types of close-ended self-completion questionnaires to LED-based lighting product manufacturers and LED-based lighting product consumers-users (e.g. individual consumers, facilities management, companies and retailers). The questionnaire for manufacturers contained 15 questions and the questionnaire for consumers contained 17 questions.

The questionnaire included questions about the following main issues:

- When do the LED-based lighting products fail or when they are replaced?
- What were the causes of these failures?
- What were the environmental and operational conditions leading to failures?
- What happens after the products fail?

Both, the manufacturer and consumer, questionnaires were translated into three languages (English, German and Spanish) for the participants based in four countries (Belgium, Germany, Spain, UK), and were distributed by several manufacturers (Ona Product S.L., Etap N.V., Braun Lighting GmbH, Riva GmbH, LED in light Ltd) in each country. The questionnaires were disseminated on-line, to a sample of 1,691 people: 396 LED-based lighting product manufacturers and 1,295 consumers of LED-based lighting products. Out of the 1,691 questionnaires distributed, 140 were completed (83 from consumers and 57 from manufacturers). As it was expected, and suggested by other studies, this data collection method had a very low response rate.

An introductory letter (appendix 5.1) was sent with the questionnaire informing participants about the aim of the study, the benefits for industry and participants, and the organisation that funded the study. The estimated completion time of the questionnaire and the confidentiality and anonymity of the participants' answers was also explained in the letter.

The two types of questionnaires (for manufacturers and consumers), and the introduction letter have been attached in appendixes 5.1 (introduction letter), 5.2 (questionnaire for manufacturers) and 5.3 (questionnaire for consumers).

Chapter 4: Case study

The case study consisted of the design process completed to eco-design a LED-based lighting product. This process was conducted and led by the author with the lighting product manufacturer (Ona Product S.L.). The company is a small (micro-SME) lighting product manufacturer based in Spain that designs and produces different types (e.g. table lamp, ceiling lamp) of lighting products for different applications (e.g. domestic, contract). The company does not have machinery in-house, they sub-contract the manufacturing of components and parts, which are assembled and packaged in the company. Complex tests and quality certifications are also sub-contracted. Due to the small size of the company they do not have a specialised team for research and development activities, although the CEO has a background in product design, and is aware of design tools, and participate in the decision-making processes of the design of the lighting products. On the other hand, the author (product designer) has been working in industry as a product designer for six years, before beginning to conduct research in sustainable product design. In the last seven years he has been involved in research related to sustainable product design, and hence is quite familiar with the tools and methods available for product designers to design products with low environmental impact. However, this case study was the first opportunity the author had *to test in a real-world industrial context* how the eco-design methods and tools suggested in the research literature (theory) worked in practice. In addition, this case study presented a good opportunity to understand better the implementation of eco-design methods and tools available to eco-design *LED-based lighting products*, in order to gain insights which could inform an eco-design approach that could be used by future product designers of LED-based lighting products.

This chapter describes and examines the eco-design process followed (case study), and has been divided in four main parts: 1) Identification of units of analysis (section 4.1), 2) case study of the design process of the LED-based lighting product (section 4.2), 3) case study of the design process of the packaging of the LED-based lighting product (section 4.3), and 4) case study of the design process of the 'system' created around the LED-based lighting product (section 4.4).

4.1 - Identification of units of analysis

This research has looked at the following specific areas of the case study for analysis: The eco-design process stages (Product Design Specifications definition, concept design, embodiment design, detail design and testing/analysis); the LED-based lighting product life cycle stages (manufacturing, use, distribution, end of life); the eco-design tools and methods used during the design process; and the product-related key issues (e.g. durability, disassembly, energy consumption) that influence the environmental impact of LED-based lighting products.

The rationale of this approach was to identify which product-related issues influenced each product life cycle, which tools and methods had to be used in each stage of the design process to reduce the environmental impact produced by these issues, and the advantages and disadvantages of each tool or method, in order to model the eco-design process followed and to develop an effective-efficient eco-design approach informed by the insights from a real-world industrial case study.

4.2 - Case study: LED-based lighting product

The case study of the LED-based lighting product has been divided in five sections, which correspond to the five stages of the design process: Product Design Specifications (section 4.2.1), concept design (section 4.2.2), embodiment design (section 4.2.3), detail design (section 4.2.4) and testing and certification (section 4.2.5).

4.2.1 - Product Design Specifications (PDS)

The first step of the design process is to define the Product Design Specifications (PDS). This section describes the process followed to define the PDS, and the insights gained based on the units of analysis previously identified (section 4.1).

The PDS will guide and delimitate (i.e. constrain) the boundaries of the creative output (i.e. solutions) created by the product designer.

The company specified the following PDS of the lighting product:

- Modular structure, so it can be customised according to customer needs.
- Aimed at contract and domestic markets.

- Indoors use, including toilets (IP44).
- Easy Light Control: Provide the exact amount of light where needed, to avoid wasting light (and energy).
- Aesthetically coherent/neutral.
- Use energy-efficient light sources (e.g. LED).
- For different lighting applications: table lamp/ceiling lamp (initially).
- Allow the possibility to incorporate different types of drivers (e.g. for different markets).
- Produce different types of light (i.e.: accent, ambient).
- Have low environmental impact.

One of the specifications of the PDS: 'have low environmental impact', comprises a number of further specifications, but since the company was not familiar with the specifications required to design a lighting product with low environmental impact, they could not specify which requirements were necessary to achieve this. The product designer (author) had to provide eco-design specifications from several sources: regulations and directives that affect lighting products (section 4.2.1.1), and eco-design guidelines (section 4.2.1.2). The eco-design guidelines also included the eco-design guidelines to extend the lifespan of the lighting product obtained in chapter 6 (Lifespan of LED-based lighting products).

4.2.1.1 - Directives and regulations

Regulations and Directives related with the environment that affect lighting products were reviewed and eco-design recommendations extracted from these to inform the PDS. These need to be complied to, not only reduce the environmental impact of the lighting product, but also to avoid fines. The most relevant are the following:

Energy-related Products (ErP) Directive 2009/125/EC (European Commission, 2009):

This directive, among other points, bans the commercialisation of inefficient light sources. The general design recommendations that can be extracted out of this directive are the use of energy-efficient light sources, and to avoid the use of inefficient light sources such as incandescent light sources.

Waste Electrical and Electronic Equipment recycling (WEEE) directive (European Commission, 2012):

This directive obliges manufacturers of electrical-electronic products to recover and re-use or recycle these at the end of life. The general design recommendations for product designers that can be extracted from this directive are the use of recycled and recyclable materials; design the lighting product so it is easy to disassemble for repair and recycling, and mark (identification codes) components and materials for easy identification (for recycling) at the end of life. The design of systems around the lighting product to facilitate its re-use and recycling can also help to comply with this directive.

Restriction of Hazardous Substances (RoHS) directive (European Commission, 2011):

This directive is concerned with the avoidance in products of specific harmful substances such as: lead, mercury, cadmium, hexavalent chromium and brominated flame-retardants (PBB and PBDE). The general design recommendations are to avoid these substances in lighting products, or to use them below the minimum thresholds agreed by the directive.

4.2.1.2 - Eco-design guidelines

Eco-design guidelines can be used at the PDS stage of the design process to provide general guidelines about features that have to be considered in the next stage (concept design) of the design process. There are many available eco-design guidelines in the literature, most of them are generic (i.e. not for lighting products in particular), but many can also be applied to lighting products, since all categories of products share many features.

The eco-design specifications used in this case study have been informed by eco-design guidelines from the literature (Chitale and Gupta, 2007; EcoSMEs, 2010; McAloone and Bey, N., 2009; Jedlicka, W., 2009; Jedlicka, W., 2010; Meinders, H.P., 1997; Nordkil, T., 1998; Shedroff, N., 2009; Siemens, 2004; Tischner et al., 2000; UNEP and TU Delft, 2006; Vezzoli and Manzini, 2008; Yarwood and Eagan, 1998).
The main eco-design guidelines considered, classified by their application per product life-cycle stage are the following:

Manufacturing stage (this also includes materials extraction and processing):

- Use as small amount of material as possible.
- Use recycled and recyclable materials.
- Use one or few types of materials in the same product.
- Avoid the use of banned toxic materials (As indicated in RoHS).
- Select local materials.
- Use materials which have established recycling networks.
- Use materials which are fit for purpose.
- When choosing recycled materials select post-consumer recycled materials.
- Avoid the use of adhesives or glues.
- Use light materials (low density).
- If using more than one material, they should be compatible for recycling.
- Use materials that are durable.
- Choose materials that achieve aesthetical properties over time (age gracefully)
- Choose materials that do not require energy-intensive processes to be shaped.
- Avoid composites and other thermostable plastics.
- Avoid using scarce and limited materials.
- Avoid use energy-intensive extraction and refinement materials.
- Avoid energy-intensive manufacturing processes.
- Choose manufacturing processes that:
    - Do not waste material.
    - Recycle the material wasted (pre-consumer waste).
    - Do not create harming emissions.
    - Do not produce liquid and solid waste.
    - Use water and energy efficiently (if at all) and use renewable energies.
- Design components that are multifunctional.
- Specify re-manufactured components.
- Design components with minimum volume.
- Eco-design guidelines to extend the lifespan of the LED-based lighting product (Please see section 6.5: Design and use recommendations to extend the lifespan of LED-based lighting products).

Manufacturing related with Packaging:

- Avoid the use of packaging if possible.
- Design packaging with minimum weight and volume.
- Design packaging to be re-used or recycled.
- Avoid the use of solvent-based inks to convey information.
- Use the amount of packaging needed for protection only (not over package).
- Criteria from previous stages already mentioned also apply here, as packaging is a product in itself.

Distribution (storage, sale and installation) stage:

- Choose efficient transport means (e.g. ship).
- Avoid Air freight.
- Design efficient distribution/logistic systems.
- Use transport which avoids damage of goods.

Use and maintenance stage:

- Design modular products so parts and components can be up-dated and repaired.
- Design easy to dismantle products to facilitate upgrade and repair of parts.
- Provide spare parts and components as well as a list with the product's components and the suppliers' references.
- Provide customer service.
- Design products which are dirt-resistant, easy to clean and require little maintenance.
- Indicate on the product how it should be opened for cleaning or repair.
- Use light and motion sensors or timers and dimmers to reduce the amount of energy used.
- Use energy-efficient light sources.
- Use energy-efficient drivers.
- Use standard components.
- Locate components that might wear out easily in accessible areas.

- Design lighting products with devices that allow the control of the quantity and quality of light in order to use the exact quantity and quality needed for each purpose.
- Specify best-in-class energy efficient components.
- Allow users to switch off lighting modules individually.
- Eliminate unnecessary product features.
- Identify and eliminate possible weak points of the product.
- Design products for safe and self-explanatory use.
- Eco-design guidelines to extend the lifespan of the LED-based lighting product (Please see section 6.5: Design and use recommendations to extend the lifespan of LED-based lighting products).

<u>End of Life stage:</u>

- Use as few fasteners as possible.
- Use the same type of fasteners.
- Use fasteners which do not require tools, or require standard tools.
- Avoid welding joints; only join permanently materials that are compatible for recycling.
- Design products so different parts (materials) can be separated easily and re-used, remanufactured or recycled depending on the component.
- Reduce disassembly steps.
- Avoid the use of coating on materials surfaces.
- Avoid the use of labels, use emboss to mark components.
- Use one single material for all the components if possible.
- Minimise the number and length of wires.
- Use one disassembly direction to avoid reorientation.
- Design for multiple detachments with one operation.
- Facilitate reuse and recycling by using standard codes for identification (marking) of materials and components.
- Design the product so it does not need to be dismantled to be recycled.
- Minimize the use of energy-intensive processes in disassembly.
- The cost of disassembly has to be less than the cost of the material recycled.

- Make sure that joining points are easily accessible and there is enough space to allow disassembly with tools.
- Include symbols or pictograms to inform about the disassembly process.
- Use detachable joints such as snap-fit, screw or bayonet joints instead of welded, glued or soldered connections.
- Select joining systems that can be dismantled after long periods of use.
- Try to concentrate in one area all components that can be recycled.
- Avoid use of joints that require energy-dependent tools for disassembly.
- Eco-design guidelines to extend the lifespan of the LED-based lighting product (Please see section 6.5: Design and use recommendations to extend the lifespan of LED-based lighting products).

4.2.1.3 - Analysis and summary of insights

This section (section 4.2.1) examines the tools and methods used during the PDS stage of the design process in the case study. This section has not considered the eco-design guidelines from regulations and directives related with packaging, only the ones related with lighting products. The design process of the packaging is briefly described and examined in section 4.3 (Case study: Packaging of LED-based lighting product).

Tools and Methods used:

At the PDS stage it was utilised two types of eco-design guidelines: Generic Eco-design guidelines, and Eco-design guidelines from three directives and regulations (RoHS, WEEE, ErP).

How the tools and methods were used:

Both types of eco-design guidelines (section 4.2.1.2) were used at the beginning of the design process to inform the PDS. Generic eco-design guidelines were used to ensure the future lighting product included a number of design features (e.g. use of recycled material, easy disassembly, etc.) that could reduce its environmental impact. Eco-design guidelines derived from directives and regulations were used to make sure the future lighting product embodied a number of design features that could contribute to comply with RoHS, WEEE and ErP directives and regulations, which were applicable to lighting products. All these eco-design guidelines were included as a list of design recommendations related with different areas (e.g. materials selection, manufacturing processes selection, maintenance, use, etc.) in the PDS.

Insights:

Eco-design guidelines are very easy and fast to apply at this stage of the design process, and they can cover different areas such as disassembly and material selection. The application of these does not require previous expertise about environmental issues. However, these can be too generic and only provide general guidance. Eco-design guidelines can provide 'general' recommendations about how the final lighting product should be, but they cannot assess different design decisions (i.e. solutions, concepts). In the case where the lighting product have to be re-designed, in addition to eco-design guidelines, a LCA-based software tool to assess the reference lighting product or the lighting product to be re-designed, was also utilised. The results of the environmental impact assessment can be used to inform where the future eco-design strategies should focus in future stages (i.e. concept design) of the design process. In this case study, an environmental impact assessment of the reference lighting product was not conducted because there was no reference lighting product to re-design, the aim of the case study was to eco-design a new lighting product. The incorporation of environmental criteria in the PDS is very important because it is at this stage when decisions will have the highest impact and it will be less difficult to implement. One of the problems found with the use of eco-design guidelines at this stage is that the specifications or recommendations provided are too general and are not quantifiable. For example, it is recommended to use recycled materials but the amount was not specified. It would have been more effective to specify the total amount of recycled content of the lighting product (e.g. the lighting product should contain 90% of recycled material and 100% should be recyclable). Therefore, all the eco-design guidelines should be provided with quantifiable targets (if possible) at the PDS stage.

4.2.2 - Concept design

After defining the PDS (section 4.2.1), the next step of the design process was to begin to define the first concepts of the lighting product. This section describes the process followed during the concept design stage of the design process, and the insights gained based on the units of analysis previously identified (section 4.1).

4.2.2.1 - Initial concept design

The initial concept was informed by the PDS (section 4.2.1). The concept that matched a higher number of PDS criteria was selected and further developed with more detailed sketches (Fig. 4.1 and 4.2). Fig. 4.1 and 4.2, explains the rationale of the design decisions made (i.e. the design features), and how each of these contribute to reduce the environmental impact of the lighting product. It can be noted how these design features contribute to the key product-related issues that affect the environmental impact of the lighting product.

The main design features of the initial concept, shown in fig. 4.1 and 4.2, are explained below:

- All electronic components were installed in one tray, which allowed the easy updating, alteration and repair, and, hence, extend the lifespan of the lighting product.
- All modules used the same matrix for extrusion, thus saving cost, material and energy.
- The housing was made of recycled aluminium, and contained LED modules, heat sinks and the energy-efficient electronic driver, which could be used with or without dimmer. Aluminium is easy to machine, and, hence, is less energy-consuming to process than other metals. It also has corrosion-proof properties for outdoors environments, durability, low weight, malleability and high conductivity to conduct heat outside LED compartments. It can be obtained from recycled sources and could be collected and recycled again at the end of life of the product. It does not require protection surface finish as it creates its own natural protection. In addition to the housing of the modules, aluminium was also used for the axis, holder and lateral covers, so the whole product could be made of one single material for easy recycling.

- The disassembly process was easy because it required basic tools only. One bolt held the whole structure together.
- It did not contain any banned toxic material (as specified by RoHS).
- Cooling fins avoided overheat of LEDs and other electronic components, thus extending their lifespan.
- The housing dimensions had been designed to contain a wide range of drivers and LED types in order to allow customization and upgrading of components over time.

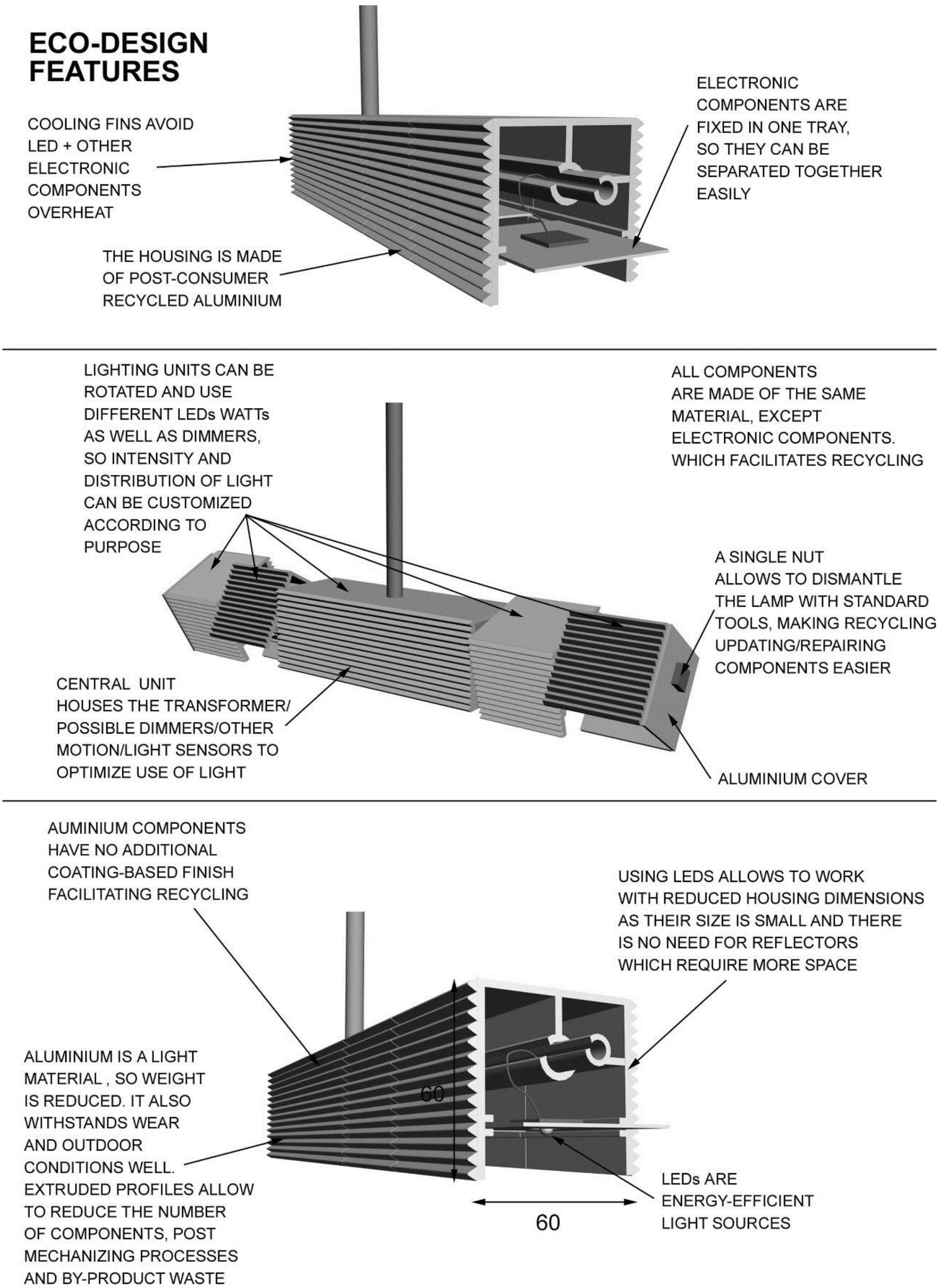


Figure 4.1. Lighting product eco-design features.

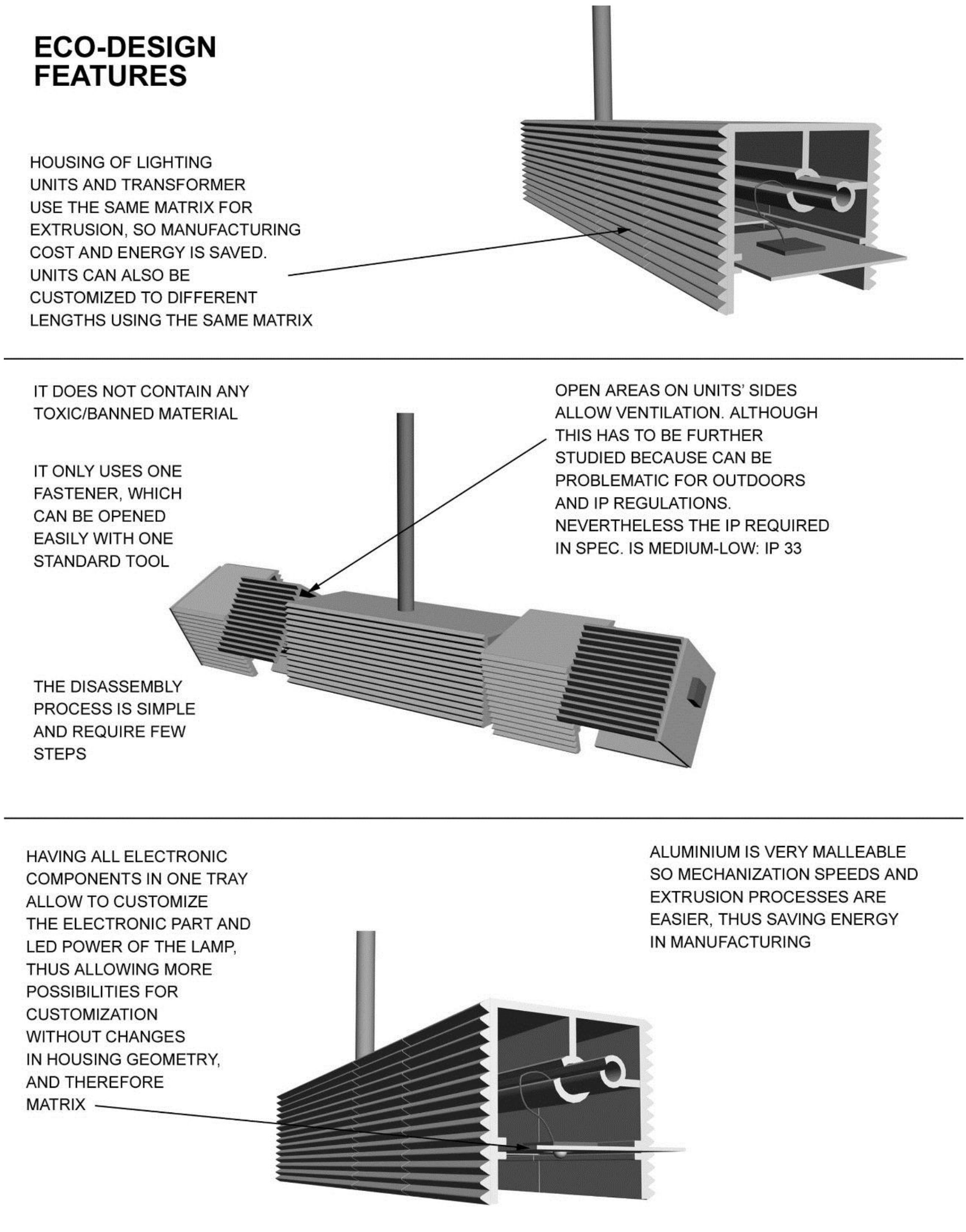


Figure 4.2. Lighting product eco-design features.

4.2.2.2 - LCA of initial design concept

Once the initial concept was roughly defined, 'what if' scenarios were used to know what the environmental impact of the lighting product would be if another material or manufacturing process was selected, and to obtain a 'feel' about what were the life cycle stages with the highest impact. As this stage of the design process, the lighting product was not defined yet and a lot of information was not available, only a streamlined LCA of the lighting product could be conducted. That is why Sustainable Minds (Sustainable Minds, 2010) software was used, a Life Cycle Assessment (LCA) screening software tool which adopts Okala impact assessment methodology (Sustainable Minds, 2015) and uses Ecoinvent database. This tool allows a quick and reasonably objective environmental impact assessment, which is translated in scores (Okala points) for easy comparison between product concepts. The scores provide the environmental impact of the concept based on the following main indicators: energy and raw material consumption, ecological damage, resource depletion, human health damage. This tool has been designed to carry out 'screening' LCAs and, since it does not require too much input data for the assessment and uses surrogates and average data from generic processes, it is very suitable for the early stages of the eco-design process, when initial concepts and their design features have to be assessed and modified quickly in an iterative process. Although the results of the assessment using Sustainable Minds are more objective and accurate than using matrix-based environmental impact assessment tools, the results are not very accurate or detailed, and should only be used to *guide* decision-making.

At this stage of the design process, it was necessary to know which was the best material choice to make the housing of the product, so the concept was assessed (using Sustainable Minds) using different materials: Aluminium, High Density PolyEthylene (HDPE) and PolyEthylene Terephthalate (PET), in order to compare the total environmental impact of the concept using these materials. These materials were selected because they were all light, corrosion-proof and easy to extrude.

One of the materials selected for the assessment was aluminium because of its corrosion-proof (for outdoors), durability, low weight, malleability (low energy required for processing) and high conductivity (to conduct heat outside LED) properties.

The other material selected for the assessment was High Density PolyEthylene (HDPE) because it is light weight, corrosion-proof, malleable, and easy to extrude. However, they usually need coating to improve their UV properties, and lose their quality (down-cycling) each time they are recycled, unlike metals (steel and aluminium) which can be recycled indefinitely without losing their properties. Also the use of polymers is not usually considered an environmentally-friendly choice because plastics use non-renewable resources and usually do not biodegrade. In addition, some versatile and cost effective thermoplastics such as PVC are toxic and its use is not recommended.

PET material was also selected because, in addition to being light weight, corrosion-proof, malleable and easy to extrude like the HDPE, it also had very good optical (transparent material) properties, which was required in lighting applications.

The following assumptions were considered during the LCA of the concept using different materials with Sustainable Minds:

- 50,000 h. was considered as the LED average estimated lifespan. This estimation was based on the useful life of the LED provided in the LED supplier datasheets.
- The concept used 4 LEDs of 3 W.
- LEDs modules and LED drivers were not considered in the assessment, because the aim of this assessment was to compare the environmental impact of the manufacturing of the housing only.

Results (Fig. 4.3 and 4.4) of the LCA showed that when aluminium was used the impact was higher than when it was used HDPE or PET, which had similar environmental impact, that is why the results of the PET assessment are not shown in the figures. Although selecting 100% recycled (instead of virgin) aluminium reduced the total impact greatly, the impact of producing recycled aluminium was similar than the impact using recycled High Density Polyethylene (HDPE) or PET. Thus when comparing the production of 100% recycled aluminium with 100% recycled HDPE, the impact of both was similar. However, the extrusion process of the aluminium was much more energy-intensive than the one used to extrude the HDPE (37.2 vs. 0.45), thus resulting in higher total impact when using aluminium (100 vs. 65 Okala points) (Fig. 4.3). When it was assumed in the LCA that both materials could not be collected and recycled at the EoL, or that they were obtained from virgin (not recycled) sources, then aluminium had even higher impact than HDPE or PET. In both cases the greatest impact stage was the use phase (which is normal in energy-using products) followed by manufacturing. The highest impact category was Ecological damage (ecotoxicity), being higher (64.94) for HDPE and PET than aluminium (55.15). The second and third highest impact categories were in human health damage (human carcinogens and human toxicity), being human carcinogens higher in HDPE or PET (21.96) than aluminium (21.23), and being human toxicity higher in aluminium (22.63) than HDPE or PET (12.06).

It was concluded that the difference of impacts between materials was not dependent on the material used (when using recycled aluminium, HDPE and PET) but on the manufacturing (extrusion) process (Fig. 4.4), being more energy-intensive in the case of using aluminium.

Although LCA-based screening software tools provides useful information about which material or industrial process to use, and which life cycle stage have higher impact, which it would not be possible with other eco-design tools such as guidelines or matrix-based tools, the information provided by this tool should be used as a guidance since it is not very accurate. This assessment could have also been conducted with more complex LCA-based software tools like Simapro, and probably results would have been more reliable and accurate, although Simapro requires more expertise and time to learn and conduct the assessment, whilst Sustainable minds is a very intuitive and easy to use tool for product designers for quick and easy environmental impact assessment.

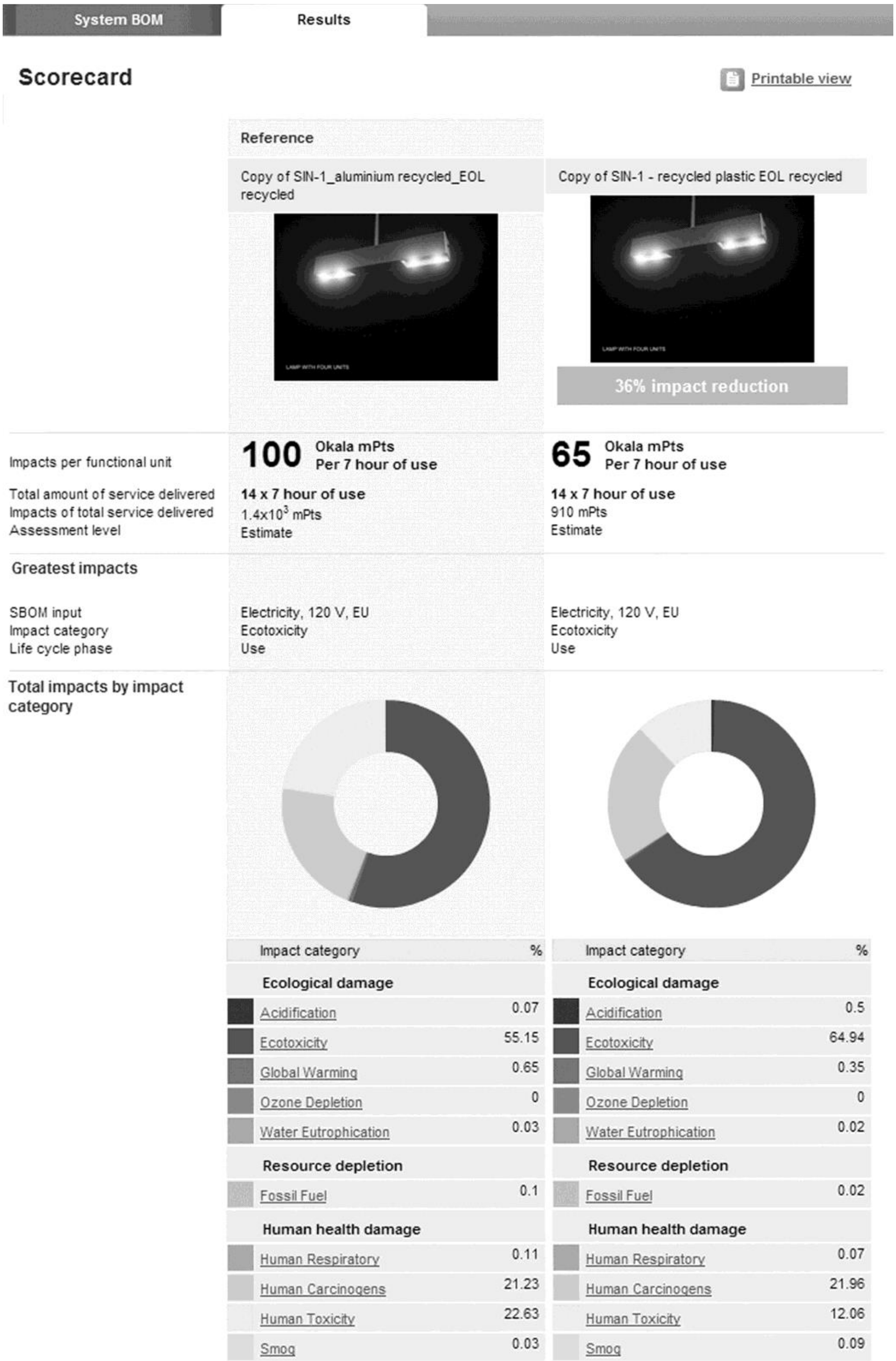
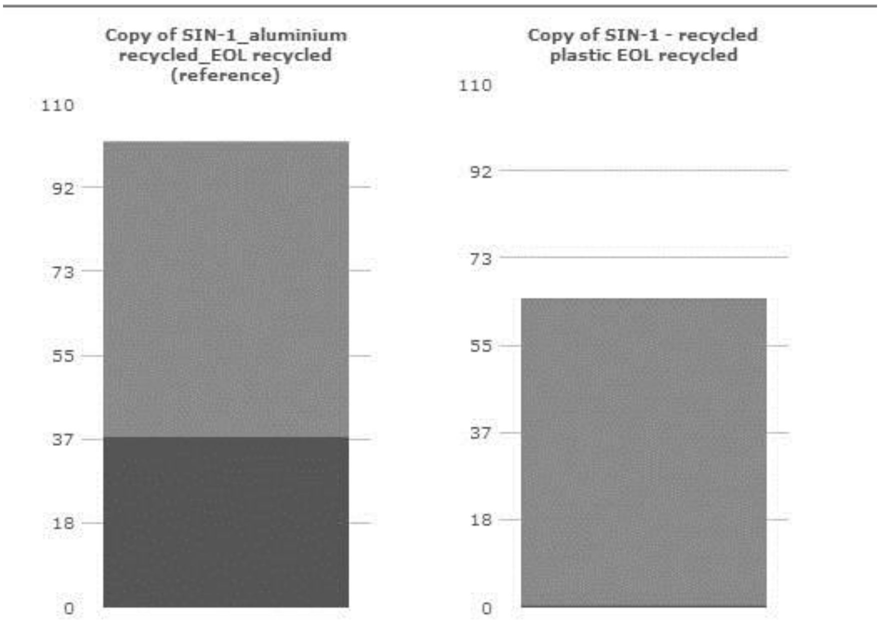


Figure 4.3. Environmental impact assessment and comparison of results using different materials (using impact category and total Okala score).



Total = 100 Okala mPts/func unit	
Lifecycle phase	mPts/func unit
End of life	0
Manufacturing	37.2
Transportation	0.00349
Use	64.6

Total = 65 Okala mPts/func unit	
Lifecycle phase	mPts/func unit
End of life	0
Manufacturing	0.454
Transportation	0.00349
Use	64.6

Figure 4.4. Environmental impact assessment and comparison of results using different materials (using impact category and total Okala score).

After the first screening-assessment of the initial concept using different materials (Fig. 4.3 and 4.4), HDPE and PET thermoplastic materials were selected to make the housing instead of aluminium, because they had less environmental impact overall. Recycled PET was finally selected because although both HDPE and PET had the same environmental impact, recycled PET had better optical, thermal and UV properties than HDPE (Ashby and Johnson, 2010). PET also allowed the possibility to use the already established recycling network of PET bottles and other PET-based products, contributing to the recyclability of the PET after disposal of the lighting product by consumers. In addition, the company had good business relations and access to a local supplier of post-consumer recycled PET.

4.2.2.3 - Final concept selection

The initial concept design (section 4.2.2.1) was modified and improved. After improvements, the final concept (Fig. 4.5) used recycled PET as the main material for the housing and presented a new architecture.

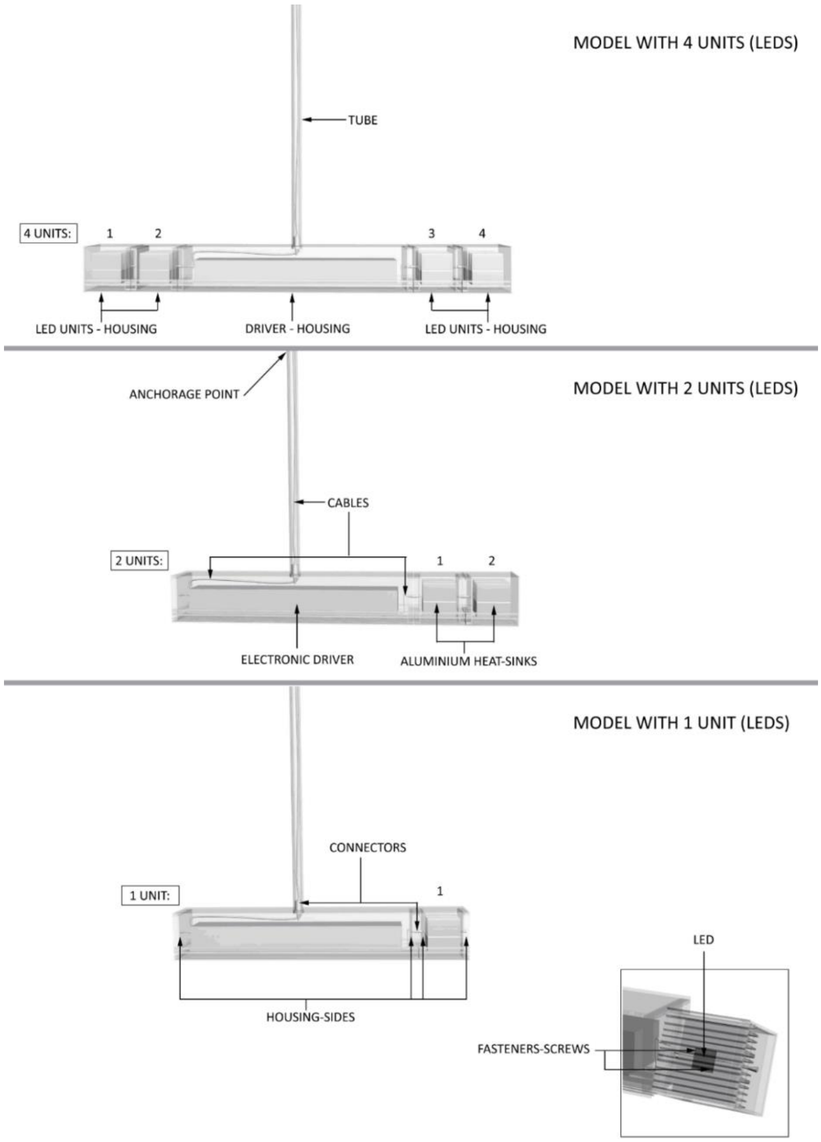


Figure 4.5. Final concept selected.

The final concept selected had the following main features:

- Housing: It was made of 100% recycled PET with no coating. As shown in Fig. 4.5, the housing had two modules: one module (driver module) housing the electronic driver, and another module (lighting module) housing the LEDs and aluminium heat sinks.
- Modular design: It could adopt 1-4 lighting modules, depending on the customer needs.
- LEDs: One LED of 4 W was used in each lighting module. In the versions of two/three/four LED units, 2/3/4 LEDs of 4 W were used.

- Tube: It was made of 100% recycled PET with no coatings. It contained the cable and was used to fix the product to different supports (i.e. wall, ceiling).
- Electronic driver: It was energy-efficient, complied with RoHS directive, and had an Ingress Protection Rate (IP64).
- Aluminium heat sinks: each LED chip was fixed in one heat sink, and the heat sink was then fixed into the lighting module. The function of the heat sinks was to diffuse the heat produced by the LED. These were made of 100% recycled aluminium.
- Other components: Fasteners (zinc-made screws), connectors (made of Polypropylene which complied with RoHS directive), and cables (Brand/model: PTFE 2501x 1,00, made of PET and copper which complied with RoHS directive).

4.2.2.4 - Consumer feedback of final concept

The aim of this survey was to obtain feedback about consumers' preferences of the final concept selected, to inform further design decisions during the embodiment design stage.

This was the first study (out of two studies) about the preferences of consumers. The second study was aimed to obtain feedback about consumers' preferences of the final prototype of the lighting product (at the end of the embodiment design stage).

The questionnaire was designed to get consumers feedback about their preferences in relation with the following topics related with the lighting product: Aesthetics, performance, lighting applications and recycling. However, in this section, only recycling has been examined because this research is mainly concerned with issues related with the environment.

4.2.2.4.1 - Methodology

Considering that the lighting product was not defined yet, that the aim of the study was exploratory, and that it was required qualitative feedback from consumers, a focus group was chosen as a research method to collect the data. The focus group was conducted with eight leading experts (practitioners and researchers) in the Swedish lighting industry who were aware of the consumers' preferences about lighting products. The Swedish company (Aaxsus AB) contributed to find the focus group participants and to coordinate the focus groups with the author. The reason why Swedish participants were selected for the focus group was because the lighting product was going to be marketed in Sweden (initially).

Focus group - participants:

- Kai Piippo: Lighting Designer, Professional Member of PLDA and founder of Ljusarkitektur.
- Clara Fraenkel: Lighting Designer PLDA, SAR/MSA.
- Isabel Villar: Architectural Lighting Designer, Industrial Designer, Msc.
- Reine Karlsson: Professor Ecodesign Lund University, TEM- Foundation, responsible for project LED-lighting and Agroforestry.
- Claes Sjöberg: Chief Physician at Lund University Hospital. Research in light and health/wellbeing.
- Jimmy Landin: VP Projects at Aaxsus. Former GlamoxLuxo Lighting.
- Tord Wingren: former CEO Ericson Mobile Platforms, CEO Samsung Electronics, present CEO of Huawei Research Center Sweden.

At this stage (concept design) of the design process, the lighting product was not defined in detail so the only information available about the product to show to the focus group participants was renders (virtual 3D representations of the product), and a list of early specifications about the lighting product.

After an oral presentation of the lighting product (with renders and the specifications list), it was provided a short questionnaire with open-ended questions (please see Appendix 4.1). This was followed by a group discussion about the main topics of the focus group, with the final aim to discuss the topics to conclude with a summary of the preferences of the participants of the focus group who were a representative sample of consumers' preferences.

4.2.2.4.2 - Results

Only the answers related with the environmental topic (recycling) have been included in this section.

Questions related with *recycling* of the lighting product:

The concept of the luminaire is that it shall be 100% recyclable. Do you think there is a demand for this kind of recyclable unit and also how important is this as sales argument?

Answers summary:

The focus group answers concluded that this was a very good argument for the public (non-private) market, and that public consumers (e.g. councils) would pay extra to purchase this type of lighting product because this extra-cost was included in their budgets. For the private market, this was of less importance from a pure sales point of view. In relation with branding and marketing this was an important design feature.

Recycling is an additional extra feature besides other general environmental arguments such as the use of LED to reduce energy consumption, and avoid unfriendly or toxic materials which are included in other lighting technologies such as Fluorescent-based lighting products.

All the answers were taking into consideration for the next stage of the eco-design process (embodiment design stage) which is explained in section 4.2.3.

4.2.2.5 - LCA of final concept

The final concept selected (Fig. 4.6) was assessed to find out its total environmental impact and the environmental impact of each life cycle stage and component.

An initial basic prototype of the final concept (Fig. 4.7) was made and its Bill of Materials (BoM) used as data-input required for the assessment with the LCA-based software tool Simapro.

Figure 4.6. Final concept.

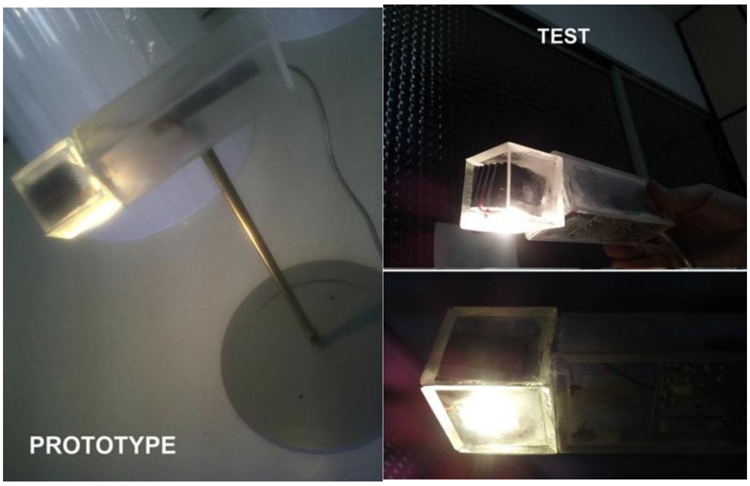


Figure 4.7. Initial basic prototype of the selected concept.

The environmental impact assessment with Simapro software requires comprehensive data about all the processes needed to manufacture the product, so a process-tree (Fig. 4.8) had to be created to describe the manufacturing processes that were needed to manufacture the lighting product.

The process-tree diagram (Fig. 4.8), illustrated which processes were used, and in which order. This diagram, unlike traditional production planning diagrams, also outlined the processes after production, such as disassembly and end of life options.

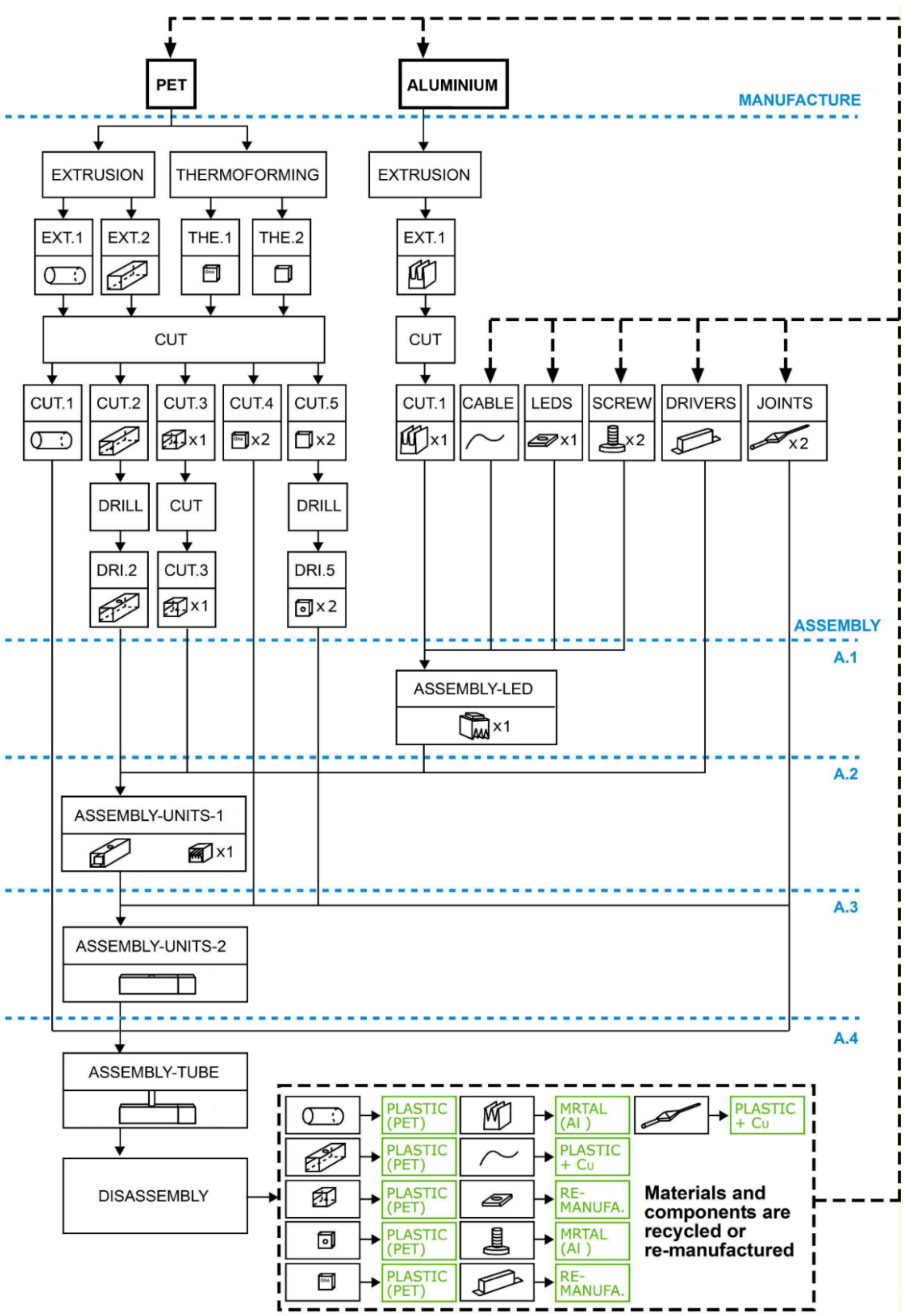


Figure 4.8. Process-tree diagram of final concept.

After the process-tree had been defined, the Bill of Materials (BoM) was created (Table 4.1), which was used as input for the LCA with Simapro software.

Component	Material	Weight (kg)
Driver housing	Recycled PET	0.120
Tube	Recycled PET	0.150
Housing of 1LED unit	Recycled PET	0.040
Heat-sink	Recycled Aluminium	0.078
Fasteners	Zinc coated	0.015
Cable	Copper	0.010
Cable	Recycled PP	0.010
1 LED unit	Various precious metals and other	0.010
Unit connectors	Recycled PET	0.006
Total		**0.423**

Table 4.1. BoM of the final concept.

Described below is the methodology used to assess the environmental impact of the final concept, and the results:

Methodology:

The LCA method (Weidema, 1997) was used to conduct the environmental impact assessment. According to this method, the following stages have to follow: 1) goal and scope of the assessment, 2) Life Cycle Inventory (LCI) of both products have to be defined, 3) Life cycle impact assessment used (LCIA), and 4) interpretation of results.

Goal of the assessment:

To define the goal, three questions needed to be addressed (Wimmer et al., 2004): why, who and what. The aim of the study was to assess the environmental impact of the final concept selected to know where (i.e. life cycle impact stage and component) the environmental impact was allocated. The target audience of this assessment were product designers, developers and managers within the company. The intended use of the results was to further reduce the environmental impact of the lighting product in further design stages.

Scope of the assessment:

During the definition of the scope of the assessment two issues had to be defined: Functional unit and system boundaries of the product. The functional unit used was 1 lumens-hour (lm-h). Regarding the system boundaries, no decision for mass inclusion was selected, so all the parts and components were included in the assessment regardless of their relative mass within the total weight of the product. The temporal, geographical and technological boundaries used within the assessment were: Temporal (5 years), Geographical (parts or components manufactured, used and disposed in Spain/Europe); Technological (average current technologies).

The system boundaries of the assessment:

Extraction of raw materials: Natural resources extraction and production of raw materials were included. Manufacture: The manufacturing of all parts and components except LEDs and electronic drivers, was included, as it was not found data available of these components. Distribution: the distribution distance assumed was approximately 300 Km within European area (in this case, Spain), and the distribution means: 3.5-16 tones Trucks. Use: the amount of electricity required to provide light to illuminate an area was 40 W per day (the product used 1 LED that consumed 6 W). It was assumed that the lighting product functioned 10 h/day during 12 months over 5 years approximately.

Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA):

In order to obtain the LCI, the lighting product was dismantled and the quantity and quality of parts and components defined. The definition included all unit processes (industrial processes) up to the gate of the manufacturing plant (also called cradle to gate assessment) included in the boundary system of the lighting product. The input/output of substances from industrial processes and materials used to make the products were obtained from databases (Dutch Input-output databases, Ecoinvent system processes, European Life Cycle Database, EU&DK Input/output database and Industry data 2.0) available in Simapro. Eco-Indicator-99 LCIA method was selected.

<u>Results:</u>

Results of the assessment (Figures 4.9 and 4.10) showed that the final concept had a total environmental impact of 14.3pt, and that the highest impact per impact category was allocated on the impact categories: 'Resources' followed by 'Human Health' and 'Ecosystem quality'. Regarding the allocation of impact per product life cycle stage, the distribution stage had the highest impact, followed by the use stage and the manufacturing stage. In the manufacturing stage, the highest impact was allocated in the manufacturing of the housings of the lighting product.

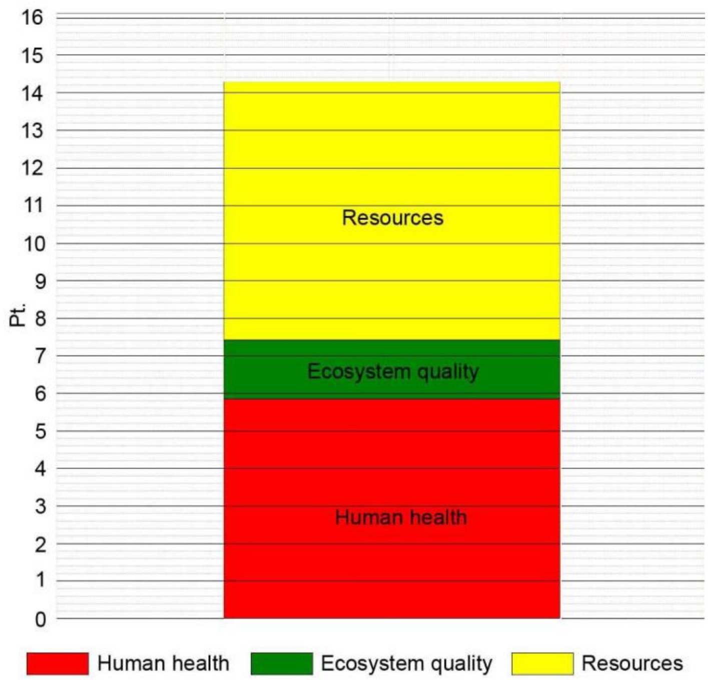


Figure 4.9. Assessment results of the final concept, based on three impact categories.

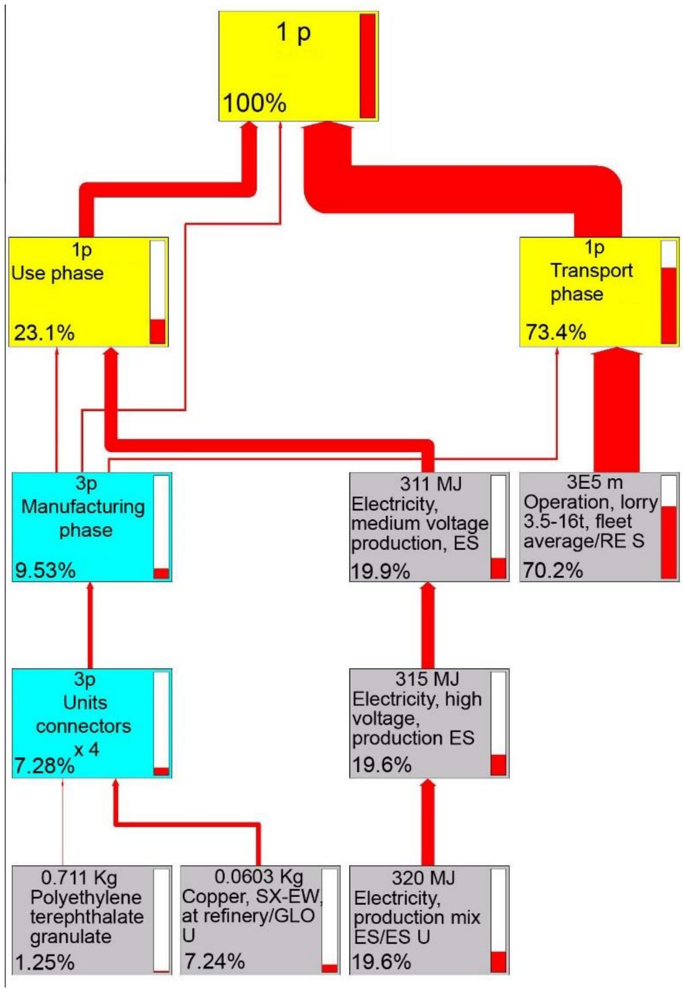


Figure 4.10. Environmental impact allocation in the lighting product life cycle stages

4.2.2.6 - Analysis and summary of insights

This section examines the tools and methods used during the concept design stage of the design process, how these were used, and the insights gained after the use of these by the author in the case study.

Tools and methods used:

At the concept design stage it was utilized Generic Eco-design guidelines, Eco-design guidelines from three directives (RoHS, WEEE, ErP), and two types of LCA-based software tools (Sustainable minds and Simapro).

How the tools and methods were used:

Eco-design guidelines (both types) were used as checklists to support decision-making in every design iteration. This meant that every time a new design decision had to be made or several design options had to be considered, the option that could comply with more eco-design guidelines was selected. In addition to this, LCA-based software tools were also used to assess and compare different design decisions (i.e. materials, manufacturing processes, and finishes selection) and concepts. The LCA results also provided information about the life cycle stages and components with the highest impact, which could guide and prioritise future eco-design strategies. Two types of LCA-based software tools were used: Sustainable Minds and Simapro. Sustainable Minds was used to assess the very early concepts and to create 'what if' scenarios to know which material or manufacturing process had lower environmental impact. It also provided estimated insights about the impact of each product life cycle stage. Simapro was used to assess the final selected concept, to understand which were the life cycle stages and components with the highest impact.

Insights:

Sustainable Minds and Simapro are different eco-design tools with different purposes. Sustainable Minds is a LCA-based software tool designed for product designers, whilst Simapro is a LCA-based software tool designed for LCA experts and environmental scientists. Sustainable Minds is easy to use, and requires less data to complete the assessment, but the accuracy of the results is low. It also allows the possibility to conduct 'what if' scenarios (e.g. what if I use aluminium instead of PET?) easily, so different concepts or the same concept in different versions can be compared easily. On the other hand, Simapro is a more complex tool, which is more difficult and time-consuming to use. It also requires a large amount of detailed data and previous knowledge about the basic principles of the LCA method in order to use and be able to understand and interpret the results of the assessment. However, it also provides more accurate and comprehensive results, and can model complex end of life scenarios to simulate possible different end of life scenarios of the lighting product. Sustainable Minds is more suitable to assess very early concepts, when the lighting product is not very defined yet and there is not enough information. Once the lighting product is more defined and there is a prototype available, then Simapro software can also be used. There seems to be a need for a LCA-based software tool that has high-quality databases and advanced assessment methods such as Simapro, whilst being easy and fast to use for product designers (Non-LCA experts) such as Sustainable Minds.

Several matrix-based tools such as green quality function deployment matrix, MET, MECO and ERPA matrixes were also trialled. The conclusion was that there was not enough information from the concept to fill-in the cells of the matrixes. In addition, the type of information asked was too specialised (e.g. environmental-related data) to be understood and retrieved by a product designer. Since the information, available for the product designer to fill-in the cells was sometimes unknown or based on very rough estimations, the results could not be considered robust enough and reliable. For example, if the matrix had been filled-in by several users to assess the same concept the results would have been different probably, which confirms the subjectivity of the results using this type of eco-design tools. The conclusion is that using this type of tools can take too much time (since you have to try find the information required), and the results are not robust or reliable, so it is not advisable to use them in real-world situations. The eco-design guidelines, on the other hand, are flexible enough to be used as a reference in any decision-making process along the concept design process. LCA-based software tools are also very useful to support product developers' decision-making processes regarding materials and manufacturing processes selection.

A focus group was also conducted during the concept design stage, and this was used to gain feedback from the final end user (consumer) to ensure the lighting product embodied the features demanded by them. Although the majority of the topics explored in the focus group were not related to the environment, one of the questions explored the market demand for lighting products made with recycled material. Additionally, the marketing department of Aaxsus AB (Distributor in Sweden) also informed that Swedish (Sweden was the first target market) end users demanded lighting products that could be dimmed, which also can reduce the environmental impact of the lighting product during the use stage, because when light is dimmed less energy is consumed, so this feature was adopted in the lighting product. Consumer surveys can be problematic for eco-designers because consumers' wishes sometimes may contradict eco-design requirements. For example, if the use of recycled materials in the housing affects the visual perception of quality of consumers, then the manufacturer will have to use virgin materials or coatings to hide the recycled material, which is not recommended in eco-design guidelines. End user feedback (in the form of interviews or focus groups) can be beneficial during the eco-design process, in order to ensure that the eco-design strategies applied will be accepted by customers when the lighting product is launched into the market. The rationale to include this type of consumer studies is that, no matter how well eco-designed a lighting product is, it will only have an impact is the consumer like and buy it.

The use of LCA-based software tools to conduct full assessment may not be necessary during the concept design stage because this can be time consuming and they do not provide results accurate enough to determine a specific eco-design strategy. Checklists based on the eco-design guidelines specified in the PDS stage can be used instead of LCA-based software tools to assess and compare concepts.

There is a need for a universal integration of LCA functions (from tools such as Simapro) in all types of CAD tools. This would make the eco-design process at the concept design stage easier and more effective, and would avoid the need for LCA-based software tools at this design stage. In addition, information based on field studies about the use and end of life stages should be linked with CAD-LCA tools in order to avoid the use of assumptions in the environmental impact assessments.

4.2.3 - Embodiment design

In the embodiment design stage the concept selected in the previous stage (concept design) was embodied and further defined. The embodiment design stage comprised the design and prototyping of several prototypes (prototype I, prototype II, prototype III, and prototype IV). During this stage the concept was modelled virtually (3D renders) and physically (3D prototypes), as well as simulated and tested to define its architecture and his performance in more detail.

Several iterations were performed during this design process stage, and several eco-design tools were utilised. In the following sections these iterations are explained with an emphasis on the relationship between the design features, design decisions, and their effect in the environmental impact of the lighting product.

4.2.3.1 - Prototype I

A first prototype (Prototype I) (Fig. 4.11) was made based on the selected concept to check dimensions and basic functionality.

Figure 4.11. First prototype at embodiment design stage.

At this stage several areas of prototype I (Fig. 4.11) were identified as needing improvement to reduce the environmental impact of the lighting product in further design iterations during the embodiment design:

- The casing was made of PMMA sheets glued together to form a rectangular box. This increased the complexity of the product (too many parts), and the materials used were not the best option from an environmental point of view.

- The current lighting product did not allow easy access for maintenance (repair) or upgrade, because there was not a practicable lid for easy maintenance.

- The driver was set inside the housing without any support-locking pins. This meant that abrupt movements could cause damage (by shock) of the driver.

- The heat sink was set inside the housing, without any support-locking pins. This meant that abrupt movements could cause damage (by shock) of the heat sinks. In addition, the joint between the LED and the casing was not a good clean solution, as there were too many components and machining processes involved.

- The modules were joined by a fastener. This fastener did not allow the units to be rotated easily, and when these were rotated, the surfaces rubbed each other creating friction and damaging the surfaces of the modules.

- There was no proper and sufficient heat convection, inside the module that contained the LEDs.

- It was not possible to attach more modules to the luminaire to increase the lighting output, because it did not feature modular design.

- Assembly and disassembly of the luminaire was difficult and required a lot of time. The luminaire could only be dismantled using destructive disassembly.

These areas were improved in following design iterations.

4.2.3.2 - 3D virtual models and simulations

A virtual 3D model was modelled (Fig. 4.12) based on prototype I (Fig. 4.11). This was quite useful because once a 3D virtual model is produced, design improvements and simulations can be done easily in a virtual environment before making expensive time-consuming prototypes. LCA can also be carried out with the LCA built-in feature of Solidworks (Dassault Systemes, 2015b). As it was explained in the literature review, provided the user knows how to use Solidworks, assessing the product after modelling it in this type of software can be very effective and convenient for product designers.

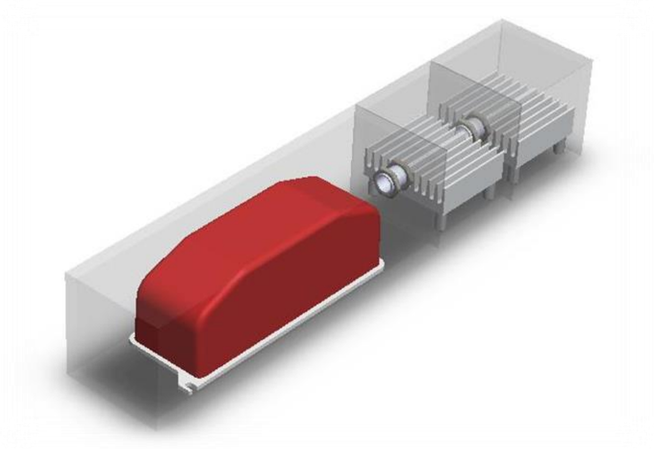


Figure 4.12. 2D virtual model of the first prototype.

One of the advantages of modelling the lighting product with CAD software like Solidworks is that, once the product has been modelled, the Bill of Materials (BoM) (Table 4.2) is automatically created which is very useful to input the data fast and accurately which needed to carry out the LCA. In addition, when the design changes, the BoM will change automatically, this in turn will change the results of the LCA too.

File Name	Quantity	Material	Total Weight	Units
Casing_Driver_assy	1	PMMA	**175.72**	g
Case_Driver-01	4	PMMA	133.8	g
Case_Driver-02	2	PMMA	18.85	g
Driver	1	PMMA	23.08	g
Casing_LED_assy	2	PMMA	**208.55**	g
Case_Driver-02	12	PMMA	113.08	g
LED_Heat_Sink_assy	2	Aluminium	95.48	g
LED_Heat_Sink	4	Aluminium	83.06	g
LED	2		0.28	g
Steel_support_pin	8	SS	12.14	g
Panel_Joint	2	Steel	1.28	g
Hex Panel Nut 3/8-32NEF x0.095 Thick	4	Steel	0.63	g
Panel stud	2	Steel	0.65	g

Table 4.2. BoM of the lighting product.

Thermal analysis:

Once the lighting product is modelled in CAD software, simulations can be conducted to predict the behaviour of the product in the expected operating environment. A thermal analysis of the heat sink used in prototype I was conducted (Fig. 4.13) to analyse if the heat sink design was thermally efficient.

In the simulated conditions, a temperature of 150°C was reached (in the LED), and the heat sink was exposed to the ambient temperature of 30°C, so heat conduction took place (Fig. 4.13).

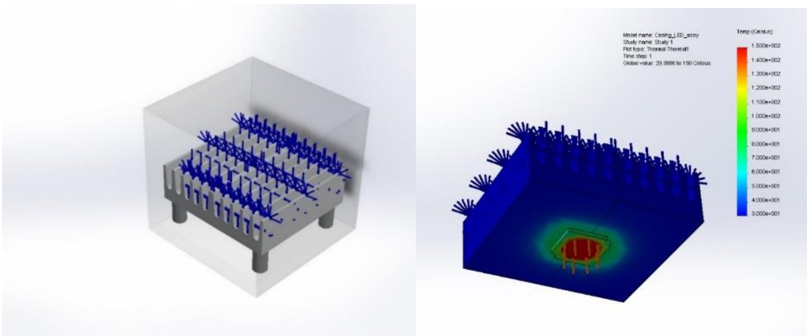


Figure 4.13. Heat sink model analysed.

Through the results (Fig. 4.13), it was confirmed that the heat sink fulfilled its function of transferring the heat generated by the LED. The average temperature around the LED contact surface was between 70°C to 50°C, so the selected heat sink was over dimensioned for the requirements of this design, so the heat sink had to be optimized (reduced in mass).

Iteration - 1:

In order to improve access to the inside of the housing for maintenance, the housing of the driver module and lighting (containing the LED) module were redesigned with a U-section profile. The ideal design to fulfil structural demands should have a square-section profile. However, a square-section profile did not allow to have access to the driver, LED, heat sink and light reflector-diffuser, so the profiles of the housing that contains the driver and the LED were designed with a U-section profile (as it is shown in Fig. 4.14). This profile was designed to be manufactured with extrusion process and could be extruded easily and required a simple injection moulding die. This solution was cost effective and could allow mass production whilst keeping a good surface finish.

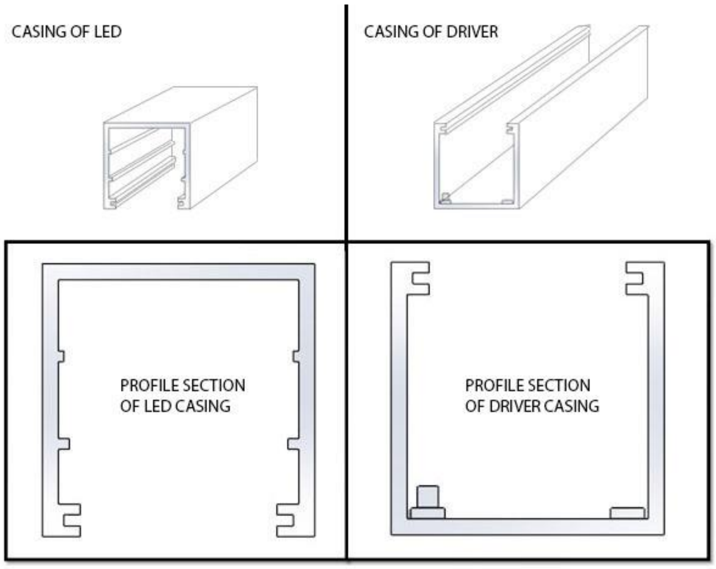


Figure 4.14. U-section profiles of the housings that contained the driver (right image) and the LED (left image).

Another key component that needed to be improved was the joint or connection between the modules. The existing joint-connector needed to be re-designed for 3 reasons: 1) It did not allow good rotation without damaging the surfaces of the modules, 2) The rotation was not complete and it was difficult to perform, and 3) Only one material should be used for the housings of the modules, and this should be recycled PET (in order to reduce the number of materials used) so the joint-connector should be made of the same material. The best option to solve this problem was to design a new snap fit joint, as shown in Fig. 4.15.

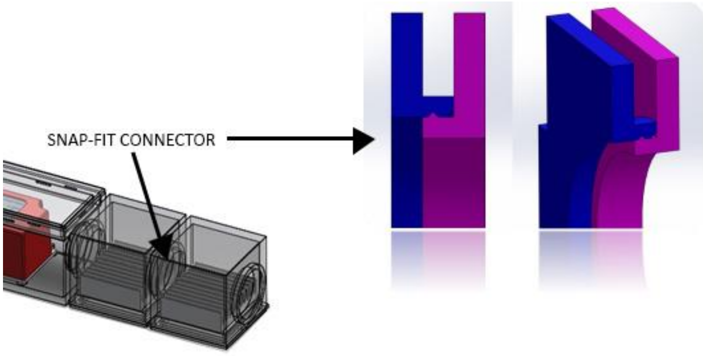


Figure 4.15. Snap-fit connector between modules.

The advantages of this type of joint-connector were:

- It used the same material (Recycled PET) as the materials used in the housings.
- Provided better stability than the previous joint.
- Saved material and energy because fewer parts were used.

When using the extrusion process to make the housings, it was only possible to shape the longitudinal side faces of the casing. The end faces had to be done as additional parts in injection moulding with snap-fit features. Fig.4.16 shows the driver module (right image) and two lighting modules assembled (left image).

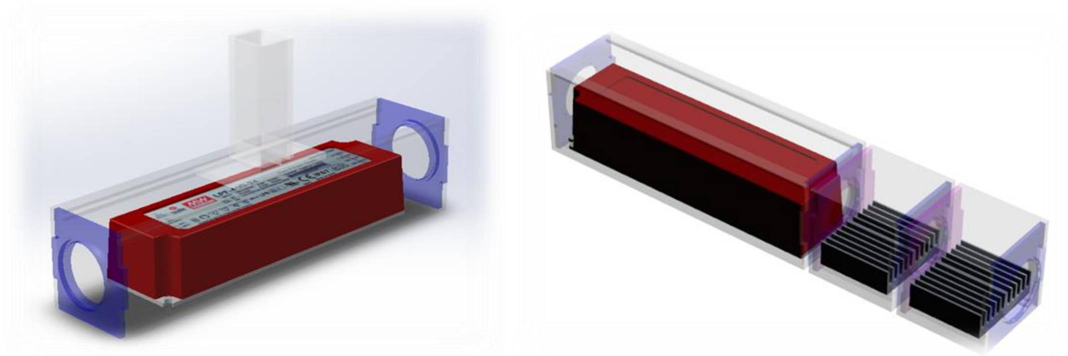


Figure 4.16. Driver module (left image) and driver module and lighting modules (right image).

<u>Iteration - 2:</u>

After the first modifications were completed in iteration 1, the housing of the module that contained the driver was modified further. Initially, the stiffness of the upper tray of the module that contained the driver was a concern; it had to be re-designed with more contact area for better load distribution to the mounting bracket to increase its durability. The modifications carried out are shown in Fig. 4.17. The new refinements also prevented dust and other substances entering the housing, which was one of the requirements specified (IP44) in the PDS of the lighting product. This was necessary in order to increase the durability of the electronic components (e.g. driver, LED) contained inside.

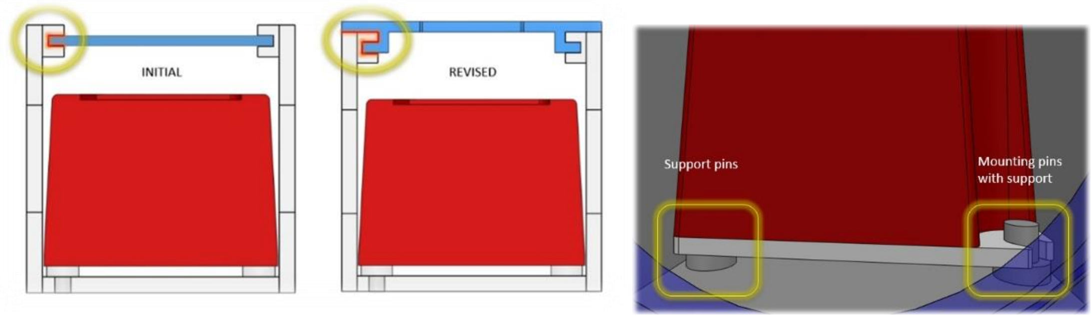


Figure 4.17. Driver module housing with mounting lid re-design (left image), and driver support and mounting pins (right image).

In prototype I the driver was not secured inside the casing so it could move freely which could damage the driver and cause a failure of the system. In this iteration the driver was arrested-supported by 2 support pins and 2 mounting pins (Fig. 4.17). Although the previous version also had pins, these were inserts in iteration 1., but to increase the structural strength and reduce the number of parts these pins were now casted on the housing.

Another improvement in iteration 2 was the LED light reflector. To avoid the light being scattered and lost on the side walls of the transparent PET housing, a reflector (Fig. 4.18) was designed. This provided more space for thermal convection for the heat sink, and narrowed the LED light beam angle. One of the main causes of failure and premature aging of LEDs is heat, that is why good ventilation of the LED was essential. Light control is also necessary in order to use the light produced where needed in order to save light and energy, that is why optical design was necessary too.

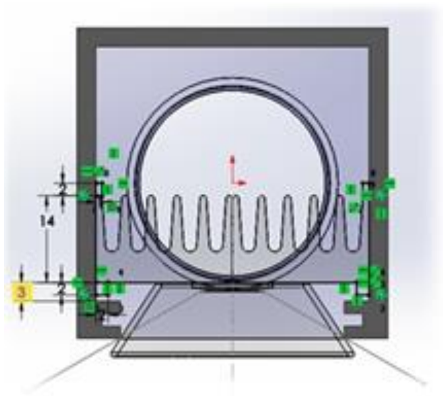


Figure 4.18. LED reflector design.

Iteration 3:

The lighting product manufacturer (Ona, 2015) completed some testing trials via suppliers with recycled PET material in extrusion machines and the material did not cool fast enough to keep the profile shape, and the extrusion supplier suggested trying injection moulding process as it might be more suitable for the properties of this material and the profile to be shaped. Another advantage of using injection moulding processes was that all the components could be made with this process and many of them probably in the same injection moulding die. Thus it was more cost-effective and more environmentally friendly since less processing and material was needed. Injection moulding was also a process that caused little waste. i.e. the material melted and injected in the injection moulding die is almost fully used.

The housing of the modules that contained the driver and LED were completely redesigned to suit the constraints of the injection moulding process, and also to include as many design features as possible in the same part. The new modules had the shape of a box opened at one side, and the joint-connector was integrated in the faces of the modules (Fig. 4.19). The new modifications reduced the tooling and manufacturing cost as well as the environmental impact (fewer parts).

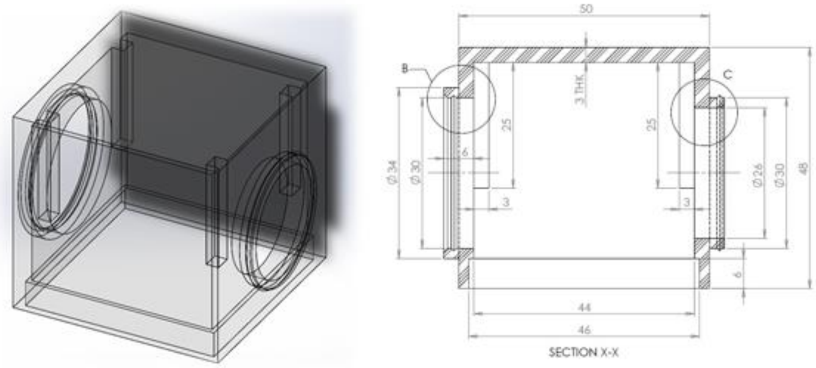


Figure 4.19. Housing re-designed for injection moulding process.

A new tray with a mounting feature was developed for the housing of the module that contained the driver (Fig. 4.20). In the previous design, the tray was just a plate and there was concern about its ability to support the load of the whole lighting product. The new tray design could take all the loads without any deflection.

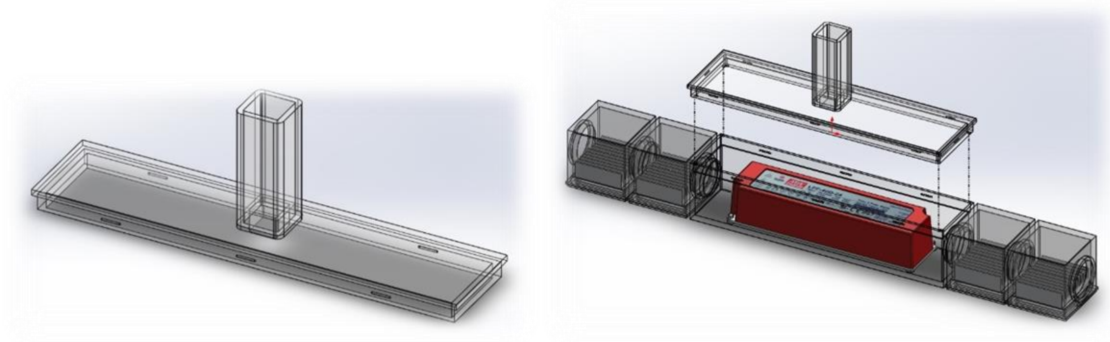


Figure 4.20. New tray design for the module that contained the driver (left image). Access to the driver after dismantling the driver module casing through upper tray (right image).

This new modification provided easy access to the driver for maintenance. The driver could be accessed by separating the tray from the main casing that contained the driver (Fig.4.20).

The modules that contained the LEDs had a similar housing design. A pair of holders replaced the tray design. These holders were designed with ingress protection features to pass the IP test. The optical element (e.g. reflector, diffuser) could be inserted into the holders and then assembled with the heat sink and LED. The holders supported the heat sink inside the casing. The assembly of the optical element and the heat sink into the lighting module casing is shown in Fig. 4.21.

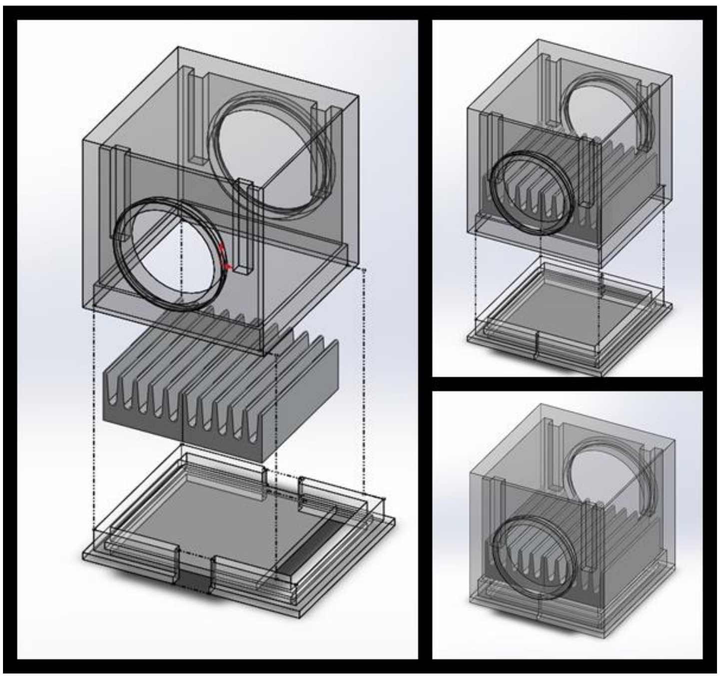


Figure 4.21. Lighting module assembly sequence.

The whole lighting product design after the design changes (iteration 3) is shown in different views in Fig. 4.22, 4.23 and 4.24.

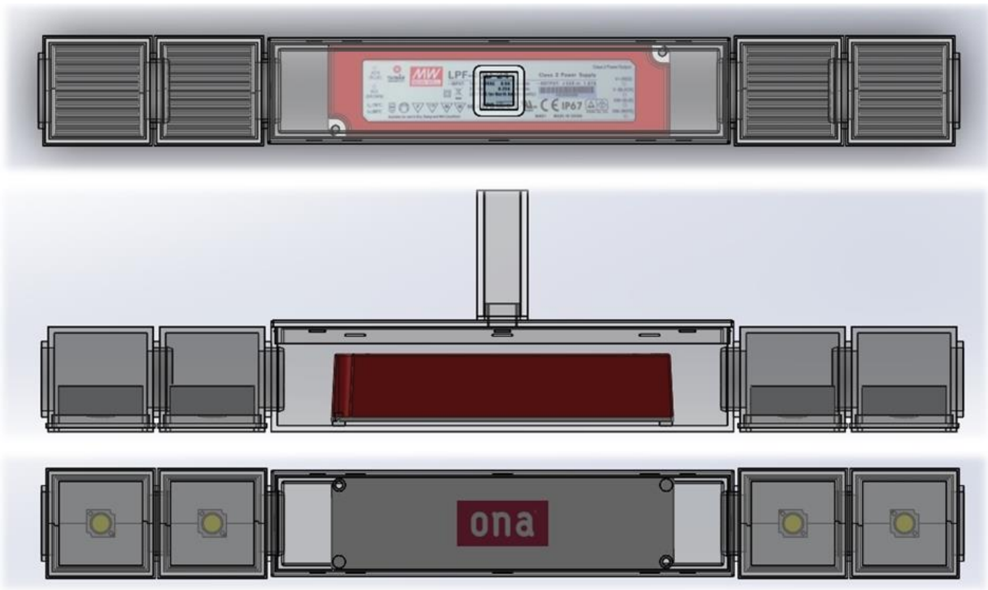


Figure 4.22. Complete Lighting product assembled – Iteration 3.

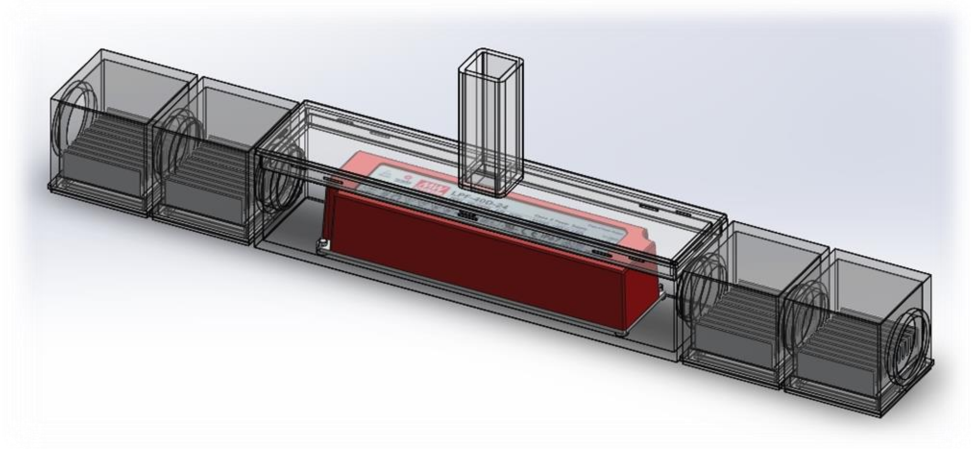


Figure 4.23. Complete Lighting product assembled – Iteration 3.

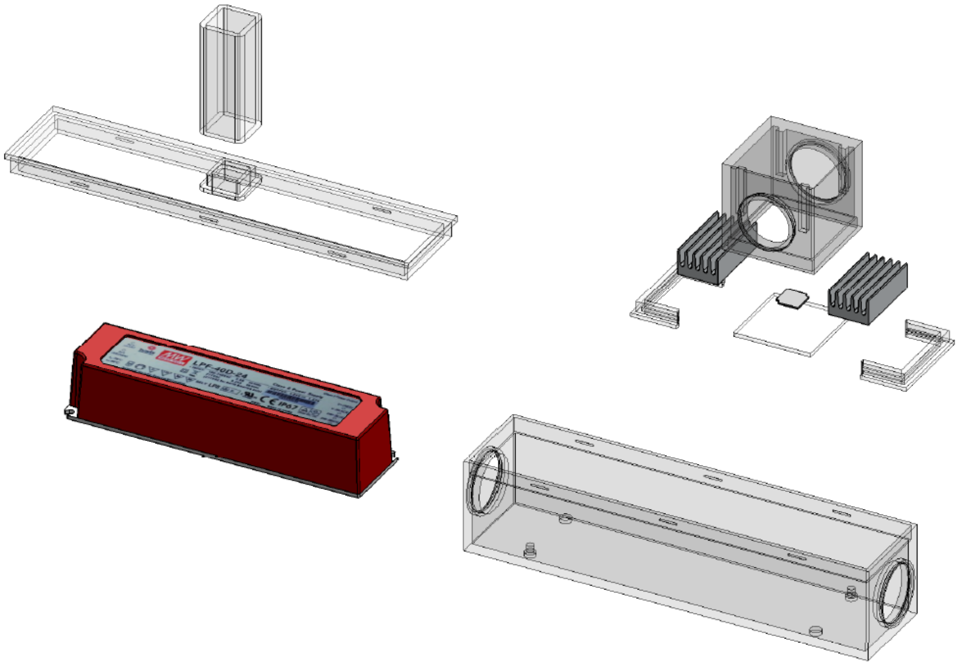


Figure 4.24. Exploded view of the complete lighting product - Iteration 3.

<u>Iteration - 4:</u>

In this iteration the heat sink design was modified. The heat sink design was changed from square section with fins to round section with pins, as it is shown in Fig. 4.25. The overall dimension of the heat sink was also changed to Ø60 mm.

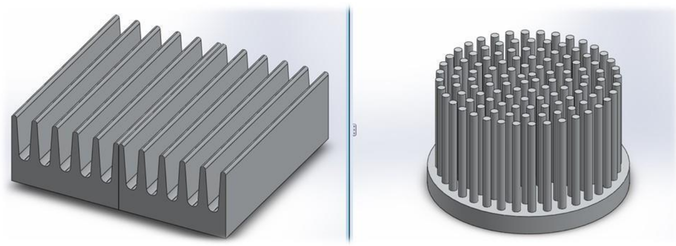


Figure 4.25. Previous and new heat sink design – Iteration 4.

The new heat sink design was analysed (thermal analysis) with ANSYS (Ansys, 2015) and Solidworks (Dassault Systemes, 2015a) to confirm it had better thermal performance than the previous heat sink design (Fig. 4.26).

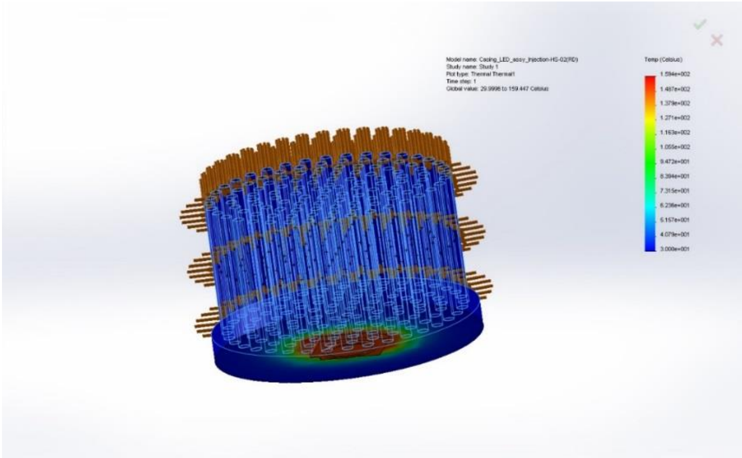


Figure 4.26. Results of the thermal analysis of the new heat sink.

Results of the analysis confirmed that the new heat sink had increased its volume slightly from 16298 mm^3. to 19263 mm^3., the change was minimal and the weight was inferior by 10%. The new design had higher surface area: from 13886 mm^2. to 23649 mm^2. This improved the heat convection up to 50%. Hence, the new heat sink had a much better thermal performance, which could ensure a longer life of the LED component and less failure rates and less maintenance costs.

As the new heat sink had a circular shape at the base, it could be mounted, unlike the previous heat sink, in the holders-components of the lighting modules. The design of the holders of the diffuser (optical elements) was modified to hold the new heat sink and the diffuser at the same time, as it is shown in Fig. 4.27. This provided easy disassembly for maintenance.

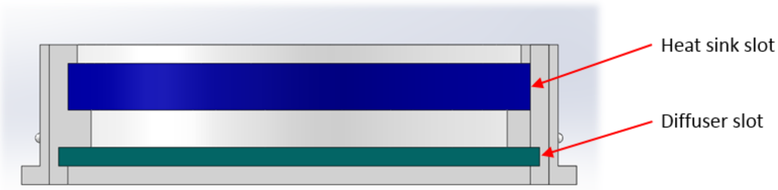


Figure 4.27. Holders design with heat sink and diffuser (optical elements) contact points.

The lighting products views after iteration 4 are shown in Fig. 4.28 and 4.29, and an exploded view is shown in Fig. 4.30.

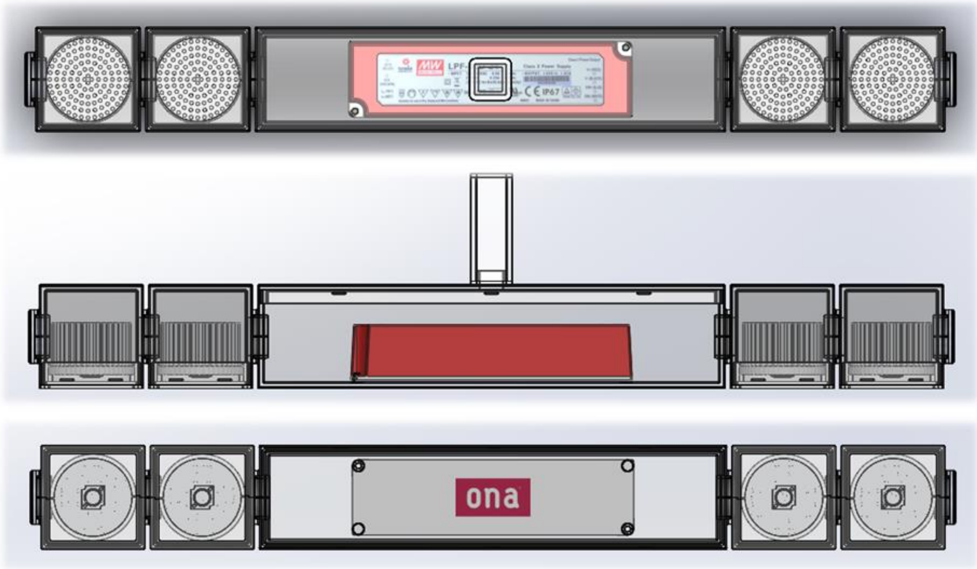


Figure 4.28. Lighting product assembled – Iteration 4.

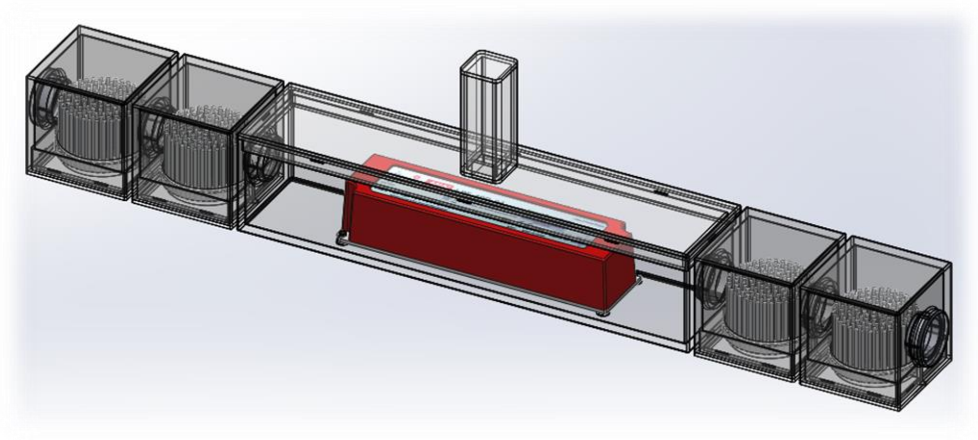


Figure 4.29. Lighting product assembled – Iteration 4.

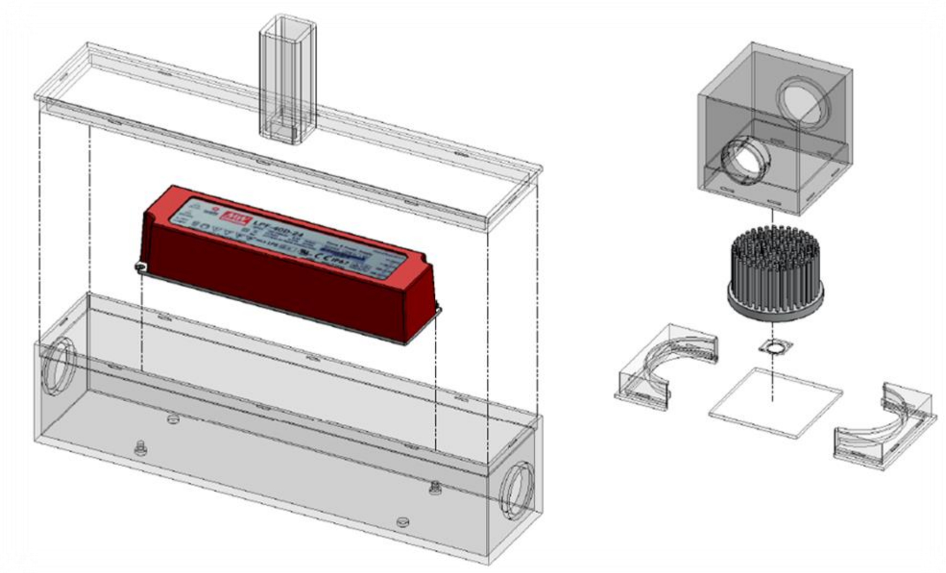


Figure 4.30. Exploded lighting product – Iteration 4.

4.2.3.3 - Prototype II

The next prototype (Prototype II) was made in Rapid Prototyping (RP) using nylon material to test the functioning and integrity of the housing of the lighting and driver modules and snap fit joints-connectors. The prototypes were also made using transparent plastic (PMMA) to be able to test the light effect in a material with similar optical properties as the PET. The prototypes made with both materials are shown in fig. 4.31 and 4.32. The lighting products could integrate from 1-4 lighting modules. Fig. 4.31 shows a prototype with four lighting modules (made of nylon and PMMA) and another one with two lighting modules (made of nylon) in the background.

Figure 4.31. Prototypes made of nylon and PMMA.

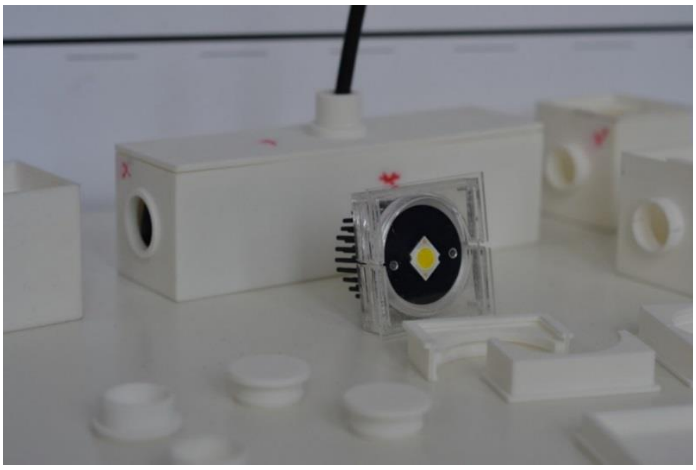


Figure 4.32. Prototypes made of nylon and detail of LED units with heat sink using transparent holders.

Evaluation:

The modifications carried out in prototype II were evaluated and compared with prototype I:

The material used in the housing had been substituted from PMMA to recycled PET (although functional initial tests were conducted with nylon). The fasteners used in prototype I had been completely eliminated. The fasteners were now made as an integrated feature of the housing (Fig. 4.33). The use of sealing adhesives and labels had been completely eliminated. Complicated design features had been avoided to simplify the manufacturing process. Since the housing was now made of a single material, the recyclability of the product had increased.

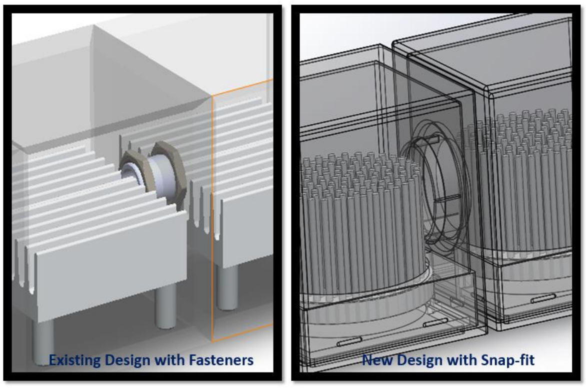


Figure 4.33. Connection-joints of prototype I (left) and prototype II (right).

The majority of the housing modules design features had been integrated to reduce the number of parts (Fig. 4.34), which could be possible when using injection moulding process, and all the housings were designed so they could be manufactured in two injection moulding dies only. Injection moulding processes (in general) requires a small amount of energy and produces minimum by product waste compared with other manufacturing processes, specially machining processes, so environmental impact had been reduced at the manufacturing stage. Disassembly of the lighting product was now easier, because all the parts were attached by snap-fit joints-connectors that did not need tools to be dismantled.

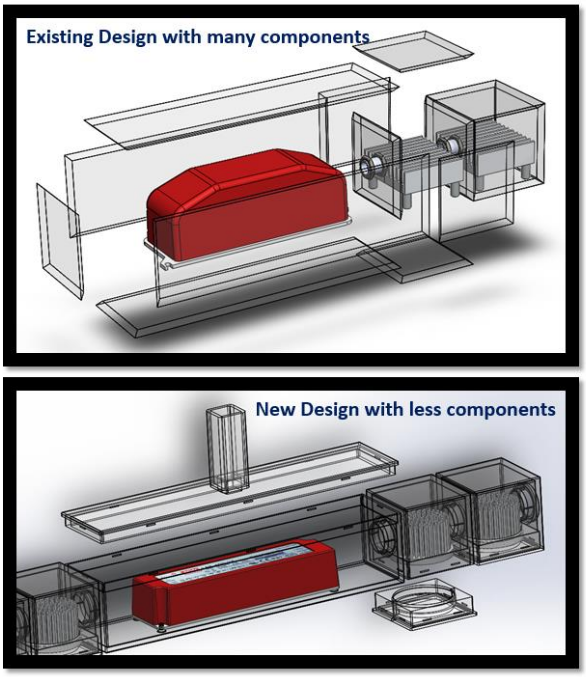


Figure 4.34. Parts and components of prototype I and prototype II.

In prototype I it was impossible to dismantle the LED or heat sink for maintenance, and too many parts and components were required to make the lighting module. Prototype II featured fewer components, due to a higher integration of functions (Fig. 4.35), which was possible thanks to the selection of injection moulding process to manufacture the module.

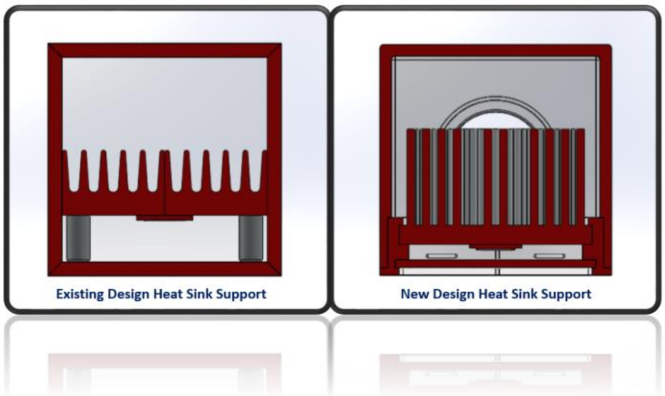


Figure 4.35. Lighting module housing design of prototype I and prototype II.

Snap fit joints-connectors were used in all the joints of prototype II. These type of joints not only allowed assembly and disassembly easily (i.e. without tools) all the parts of the luminaire, but also improved the Ingress Protection (IP44) of the lighting product, which was one of the requirements of the PDS. All the joints used in the housings were designed for Ingress Protection, as it is shown in Fig. 4.36.

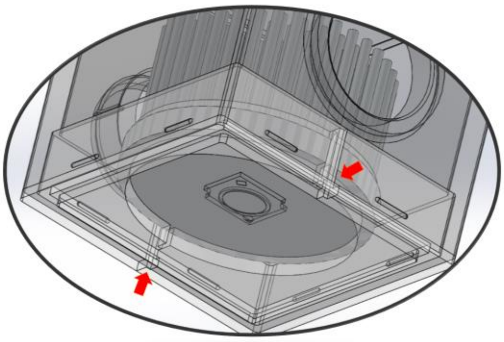


Figure 4.36. Ingress Protection (IP) features.

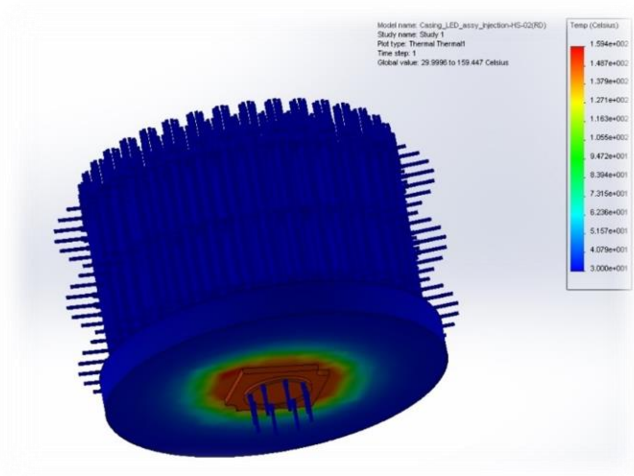


Figure 4.37. Thermal analysis results of heat sink used in prototype II.

The performance of the heat sink was also improved. Although the volume of the new heat sink had increased slightly (from 16298 mm³. to 19263 mm³), the weight had been reduced about 10%. The new design had a substantial increase of the surface area (from 13886 mm² to 23649 mm²), which improved the heat convection up to 50%, so the thermal efficiency had been improved and mass had been reduced with the new heat sink design (Fig. 4.37).

4.2.3.4 - Comparative LCA of prototype I and prototype II

The environmental impact of Prototype II was assessed and compared (using LCA) with Prototype I, which was used as a reference at the beginning of the embodiment design process. The aim of this assessment was to find out if the modifications implemented in prototype II had reduced the total environmental impact of prototype I, and in which life cycle stages and components this impact had been allocated.

The assessment performed was a cradle to grave assessment which comprised all (materials, manufacturing, distribution, use, and end of life) product life cycle stages of both lighting products, except the packaging, which had not been considered in the assessment. It had been assumed that both luminaires were distributed 300 km. by road in a delivery van of less than 3.5 tonnes capacity. Prototype I used 2 LEDs with an energy consumption of 6 W each. Prototype II used 2 LEDs with an energy consumption of 4 W each. The lifespan considered for both luminaires was 50,000 h. which was based on the lifespan of the LED used as specified by the LED supplier.

The assessment was carried out using the LCA-based software tool Simapro, and using the Eco-indicator 99 Life Cycle Impact Assessment (LCIA) method.

<u>Results:</u>

The results (based on the following end point damage categories: Human Health, Ecosystem quality and Resources) of the life cycle assessment showed that Prototype I, which was designed at the beginning of the embodiment stage, had higher total environmental impact than Prototype II (Fig. 4.38 and 4.39). The life cycles stages with the highest impact were: the 'use' and 'manufacturing' stages, where Prototype I had higher environmental impact than Prototype II.

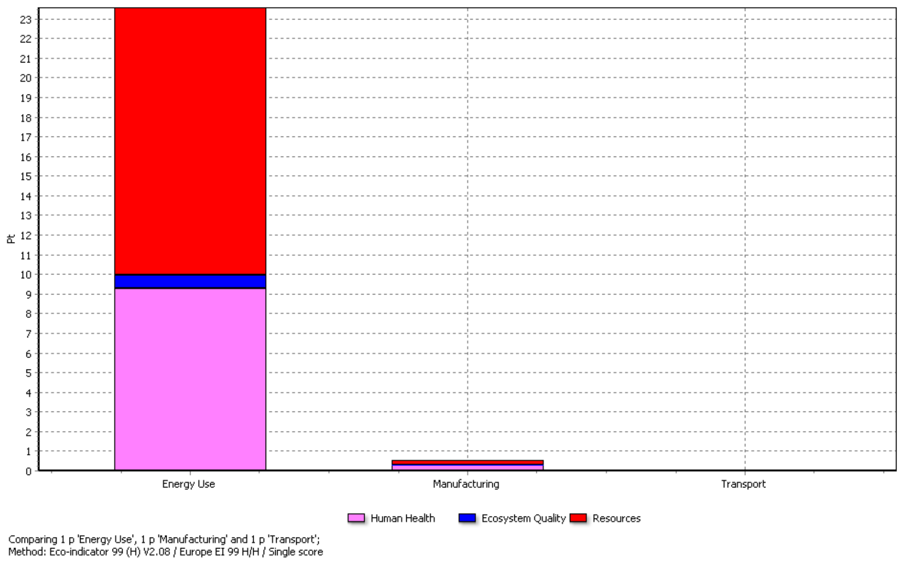


Figure 4.38. Environmental impact of prototype I life cycle stages based on end point damage category.

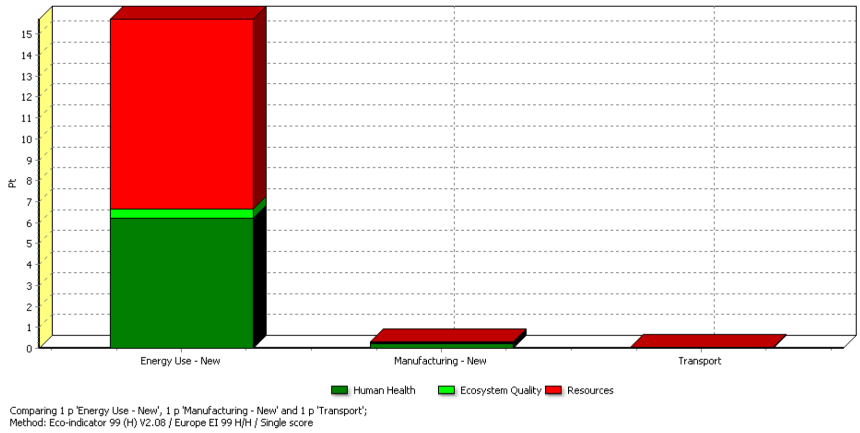


Figure 4.39. Environmental impact of prototype II design life cycle stages based on end point damage category.

The higher impact of the 'use stage' was caused by using LEDs with higher Wattage (6 W vs. 4 W), and the higher impact of the 'manufacturing stage' was caused by the higher impact of the manufacturing of the housing, heat sink and driver. The LEDs had nearly the same impact (Fig. 4.40 and 4.41).

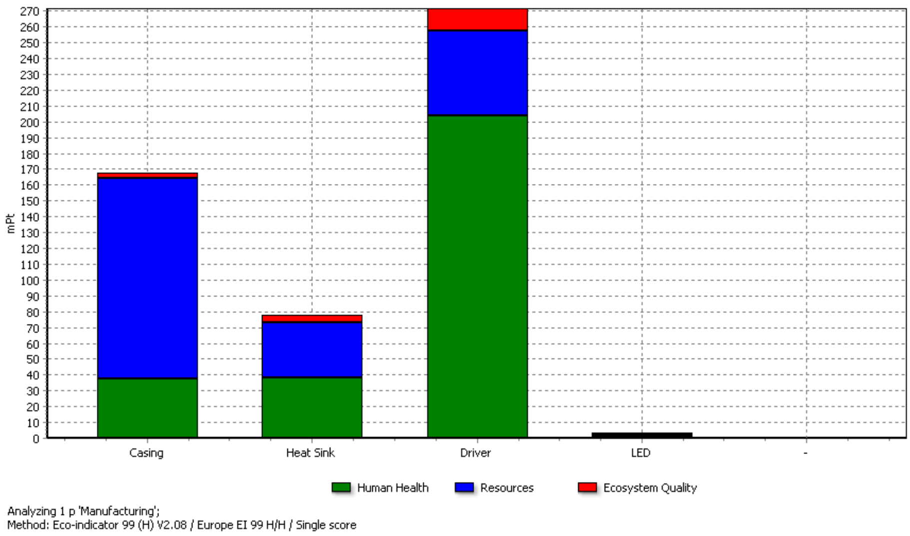


Figure 4.40. Environmental impact of the manufacturing stage of prototype I based on end point damage category.

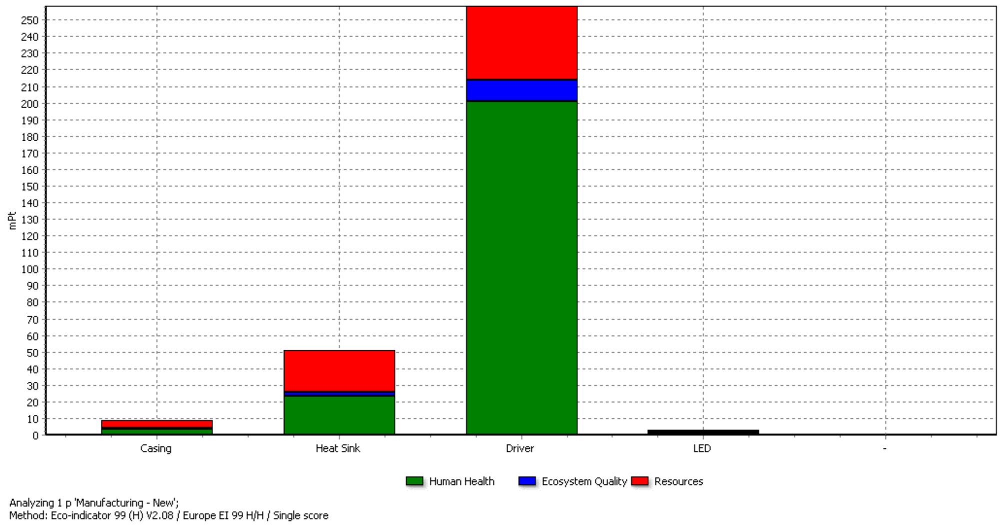


Figure 4.41. Environmental impact of the manufacturing stage of prototype II design based on end point damage category.

The life cycle stage with the highest impact was the 'use stage' in both lighting products which is typical in energy-using products, and lighting products in particular. This means that the eco-design efforts should be focused towards reducing this life cycle stage first. Sometimes, however, the 'use stage' impact cannot be reduced further. For example, if highly efficient light sources are used (e.g. LEDs) and the lighting product efficacy is high, there is not much scope for further improvements unless smart control systems are adopted, or the energy needed is sourced from renewable energy sources (e.g. solar, wind).

The manufacturing stage was the second stage with the highest impact, and all the components used in prototype II (except the LED that had similar impact) had substantially less environmental impact in comparison with prototype I. This is because less material was used, and also because the material used was shaped by fewer and more efficient (i.e. less use of material and energy to process) manufacturing processes. The new driver selected was lighter, and the new heat sink was lighter and more efficient (i.e. less energy consumption). The previous heat sink had to be extruded, cut and glued (2 parts), the new one was produced in one single process where all the parts were manufactured at the same time. It has to be noticed that machining processes have a high environmental impact and, in general, should be avoided.

Please see Appendix 4.2 for more details about this LCA.

4.2.3.5 - Prototype III

Through comparing (with a LCA) prototype I and prototype II it was confirmed that prototype II had less environmental impact so a fully functional more detailed prototype based on prototype II (Fig. 4.42) was made. Prototype III also took into account the feedback from the marketing department of the company (Ona Product S.L.) which suggested that fully transparent PET material used in the casings would not be well received by the market, because the consumers did not like to see the internal electronic components of the luminaires, so the material used in this prototype had a frosted finish in the casings so end users could not see the inside. In subsequent prototypes, the tube and base that support the casing were also made in frosted finish PET (Fig. 4.43).

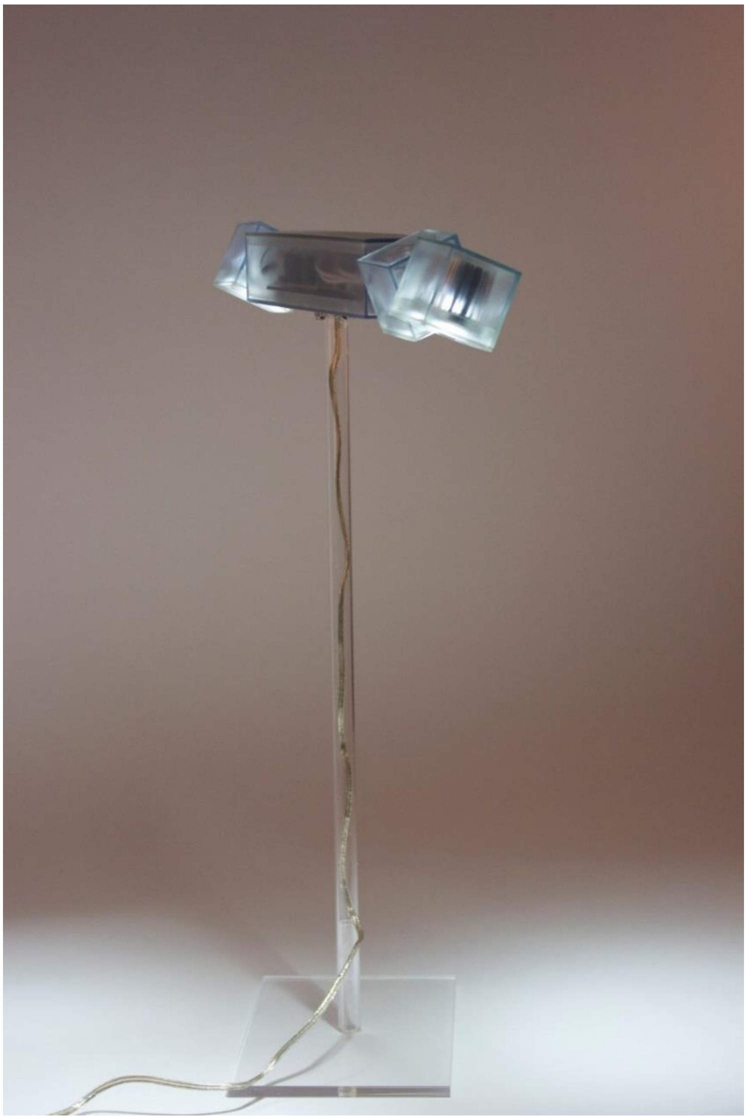


Figure 4.42. First full-scale functional prototype after embodiment design stage.

Figure 4.43. First full-scale functional prototype after embodiment design stage – with frosted finish in all parts (left image). First full-scale functional prototype after embodiment design stage - with frosted finish in all parts (right image).

4.2.3.6 - Consumer feedback of prototype III

In order to obtain end user feedback about prototype III (Fig. 4.43), a small survey was conducted.

Aim:

The aim of the survey was to show prototype III to consumers to know their opinion about prototype III, in order to identify areas that could be improved further to suit consumers' preferences to increase future sales, before the lighting product was totally defined.

Methodology:

The method used to collect the data consisted of exhibiting the prototype in a stand at the Northern Lights Stockholm trade fair (February, 2014), and ask a sample of random people who stopped at the stand (28 fair visitors: 22 males and 6 females), a number of questions about the product through a structured questionnaire.

Results:

Explained below are the main insights obtained from the survey that could influence eco-design decisions. Other insights related with cost and appearance have not been included since they did not affect the environmental impact of the lighting product directly.

- The finish quality of the casing is rough.
- In general, participants are not interested in buying lighting products with low environmental impact at a higher price.
- The structure of the luminaire does not seem solid enough. The tube that supports the modules can flex easily.

Design recommendations:

Based on the main consumer insights obtained from the structured interviews, design recommendations for the next version of the prototype were defined:

- Improve the finishing of the recycled material used to make the housings.
- Reduce the cost of the product.
- Improve the strength of the lighting product structure.

The insights and design recommendations from the consumer survey were added to the manufacturer and product developer (author) insights and design recommendations, which informed prototype IV. Only the aspects that could be related with eco-design decisions have been discussed.

The main insights obtained from the assessment conducted by the manufacturer and the product developer (author) were the following:

- The tolerances of some of the snap-fit joints used in the housing of the lighting modules (to have access to the LED and heat sink) were too tight, which did not allow a smooth assembly-disassembly of the parts, and this could cause breakage of the part (Fig. 4.44).

- The snap-fit joint-connector used to join-connect the modules allowed disassembly of the modules without any tools too easily. This feature, which was beneficial for repair and recycling, did not allow the lighting product to comply with CE safety tests, because it allowed to dismantle the modules too easily (with one hand) and without tools, which could be unsafe, because the modules were connected with electric wires.

- The connector-joint should not turn more than 360° because it could cause wire breakage, and it will not pass the CE safety tests, in particular the test: AENOR EN 60598-1: 2008.

- The lighting units should be able to be switched on/off individually, which would allow total light control, to save energy during the 'use stage'.

- The tube-pole used to support the housing was difficult to make or obtain it in 100% recycled PET. In addition to this, when this part is made of plastic it flexes and does not seem solid enough, so it might be necessary to change the material type used in this part.

- The snap-fit joint-connector between modules did not attach the modules perfectly, because the tolerances were not ideal.

- Avoid advanced features that add cost and do not contribute to reduce the environmental impact of the product such as wireless remote control and touch-based switch.

Figure 4.44 Breakage of the lighting unit casing because of tight tolerances in the joints.

Design recommendations:

- The tolerances of the snap fit joints of the lower tray that allow access to the LED and heat sink in the lighting module have to be modified to allow a smoother fit to extend the durability of the component, and hence the lifespan of the lighting product.
- Re-design of snap-fit joint-connector, to avoid rotation over 360°, and avoid easy disassembly so it cannot be dismantled with one hand without tools. This will avoid wire breakage and hence extend the lifespan of the lighting product, and comply with CE safety regulations regarding easy disassembly with one hand.
- Allow individual switch on/off of each lighting unit/module to increase light control and save energy.
- Improve the finish of the material used in the housings. Recycled material may have less finish quality which can affect sales. If recycled materials are used, these have to have a good finish to be able to compete with lighting products made of non-recycled materials.
- Reduce the cost of the product, whilst maintaining low environmental impact.
- Improve the strength and stability of the structure, in particular the joints between the housings and the pole, and the pole and the base. Robust design will increase the durability of the lighting product and therefore its lifespan.
- Remove touch-based switch components and remote wireless control functionalities, because these devices do not help to reduce energy during the 'use' stage but increase the environmental impact of the lighting product.

4.2.3.7 - **Prototype IV**

Following the design recommendations suggested in the previous section (section 4.2.3.6), modifications were implemented in the final prototype (prototype IV). Explained below are the modifications implemented to fulfil the design recommendations.

The tolerances of the snap fit joints of the lower tray that allow access to the LED and heat sink in the lighting module have to be modified to allow a smoother fit:

The tolerances were changed so the lighting modules could be joined easily without being loose or excessively tight, leading to breakage.

Re-design of snap-fit joint-connector, to avoid rotation over 360°, and avoid easy disassembly so it cannot be dismantled with one hand without tools:

Two standard snap-fit joints connectors were selected and trialled after the one previously used. The first one was made of Teflon (Fig. 4.45-left image), and the second one aluminium (Fig. 4.45-centre image). The one made of Teflon was used in the prototype exhibited and presented some problems: 1) It was not made of recycled PET (same material of the housing), 2) the joint was not robust enough, and 3) the joint allowed rotation further than 360°. The joint-connector made of aluminium was more robust and it connected the modules tightly, but it also allowed rotation of the modules over 360°. In addition to this, the materials used were not recycled PET, and ideally it should be used the same material used in the housing to facilitate recycling.

Figure 4.45. Snap-fit joint connector made of Teflon (left image). Snap-fit joint connector made of aluminium (centre image). Snap-fit joint connector made of recycled PET (right image).

A new snap-fit joint-connector was therefore designed (Fig. 4.45-right image) to solve these problems. This joint-connector allowed a 360° maximum rotation of the lighting modules, and it could be dismantled as easily whilst passing the CE safety tests. It was made of recycled PET and could be produced in the same injection moulding dies with the other parts, to save environmental impact and cost. The new snap-fit joint connector geometry required specific design features (Fig. 4.46: Hole with special shape) in the modules housings to avoid rotation over 360°.

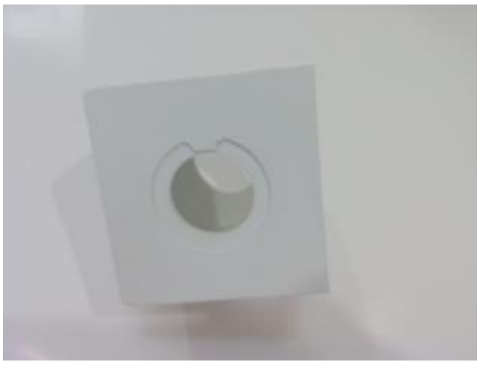


Figure 4.46. Design feature in the hole of the housing for the new joint-connector.

Allow individual switch on/off of each lighting module:

The previous prototype did not allow individual switch on/off of each lighting module, so the user did not have total light control, which is directly related with the amount of energy used and also with the environmental impact caused by the luminaire.
One of the problems with trying to allow individual switch on/off of each LED contained in each lighting module is that there is not enough space inside the lighting modules to house the components needed. The lighting modules already house the heat sink, LEDs, reflector and diffusor so there is not much space left for additional components.

However, the integration of dimmable drivers is possible, and the dimmer also allows light intensity control, which is equivalent to the switch on/off of individual lighting modules to produce more or less light according to the lighting needs. The use of dimmable drivers was also suggested by the Swedish distributor (Aaxsus AB) of the lighting products as an essential feature in the Swedish market.

Improve the finish of the material used in the housings:

One of the problems of using 100% recycled PET was that the finish was not good enough for the market niche targeted (high end design lighting products). Although trials with different suppliers were conducted to find the 100% recycled PET material with better properties to be shaped in injection moulding with high-quality finish, the quality was not good enough. However, the addition of colorants could improve the finish, and this was also required by consumers (opaque colours wanted) so all the problems could be solved by including additives (Fig. 4.47) and producing the housings in opaque colours (black and white colours initially).

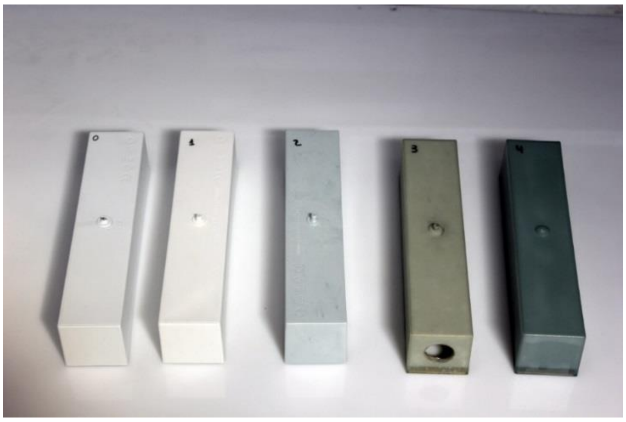


Figure 4.47. Housing-additives gradation: Housing with no additives (right housing) to maximum addition of additives (left housing)

Reduce the cost of the product:

In order to reduce the cost of the product, the manufacturing process was analysed to find areas where cost could be reduced whilst maintaining or reducing the environmental impact of the lighting product. After assessment of the manufacturing process several potential areas for cost reduction were implemented:

The initial heat sink selected (Fig. 4.48-left image) was substituted by a cheaper new standard heat sink (Fig. 4.48-right) with similar thermal efficiency.

Figure 4.48. Initial heat sink (left image) and final heat sink (right image).

Some of the design features of some parts were too complex and made the fabrication of the injection moulding dies too expensive. Some features and tolerances of some parts were modified, as suggested by the injection moulding dies manufacturer, to reduce costs. In addition to this, as many parts as possible were included in each injection moulding die to reduce the number of injection dies and hence manufacturing costs, which also reduced the environmental impact as less parts (i.e. materials and energy) and manufacturing processes were needed.

Another area used to reduce cost was the LED electronic driver. The cost of dimmable high quality electronic drivers (Fig. 4.49-left image) that were selected initially was high, however it was possible to select non-dimmable drivers with acceptable quality and make them dimmable with an additional circuit which could also provide other functionalities such as sensors and wireless controls (Fig. 4.49-right image). Using a combination of a non-dimmable driver and a circuit could save costs and give the possibility to add new functionalities (e.g. sensors) that could save further energy.

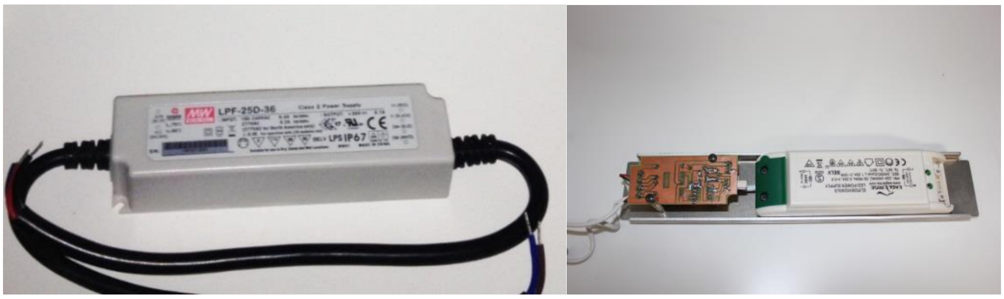


Figure 4.49. Initial driver selected (left image). Final driver selected with circuit integrated (right image).

<u>Improve the strength of the luminaire structure, in particular the joints between the housing and the pole, and the pole and the base:</u>

The joints between the tube-pole and the housing modules and the tube-pole and the base (Fig. 4.50), were not robust enough, and customers stated that it did not seem strong enough and safe.

Since it was not possible to extrude the tube required in the material selected for the housing (100% recycled PET), and round-section tubes made of plastic would never provide a solid stiff junction, a tube made of recycled aluminium was used instead of recycled PET (Fig. 4.51). The recycled aluminium tube is stiffer and provides a solid joint with the modular housing and the base. The marketing department of Ona Product S.L. and Aaxsus AB confirmed that aluminium tube was fine in terms of customer preferences so it was substituted. Aluminium could also be fully recycled and there was a well-established infrastructure for collection and recycling of aluminium.

Figure 4.50. Modules housing-tube and tube-base joints of prototype exhibited in the fair.

Figure 4.51. Final prototype with tube-pole made of recycled aluminium.

Improve the stability of the lighting product:

The base of prototype III (Fig. 4.50) was made of recycled PET but it was not heavy enough to provide good stability to the lighting product. The base of prototype IV was made of recycled aluminium (Fig. 4.51) which provided a heavier base with more stability.

Remove touch-based switch components and remote wireless control functionalities:

Touch-based switch control was installed some versions of prototype III (Fig. 4.52-left image: green dot). This feature was built into the luminaire because it was supposed to appeal some customers and be more convenient for the user, however it increased the cost and it also increased the environmental impact of the lighting product. In prototype IV the touch-base switch control was substituted by a traditional switch control installed in the cable.

Figure 4.52. Touch-based switch controls built into the housing (left image). Wireless remote control testing (right image).

Wireless remote control was another feature built into prototype III. Although this function could be added at no extra cost in the luminaire (apart from the remote control device) (Fig. 4.52-right image), and provided more comfort to the user, it did not add any advantage in terms of environmental impact reduction, on the contrary, it added extra impact because of the manufacturing of the remote control device, so it was not included in the luminaire.

4.2.3.8 - Analysis and summary of insights

This section examines the tools and methods used during the embodiment design stage of the design process; how these were used, and which insights were gained after the use of these by the author in the case study.

Tools and Methods used:

During the embodiment design stage, Generic eco-design guidelines were used, eco-design guidelines from three directives (RoHS, WEEE, ErP), one type of LCA-based software tool (Simapro), modelling and simulation tools (Solidworks) and the 'assessment of design features' method.

How the tools and methods were used:

Eco-design guidelines (both types) were used as checklists to support decision-making processes in every design iteration. This means that in every design iteration, all the eco-design guidelines were checked to fulfil all the eco-design guidelines from the PDS. In addition to this, a LCA-based software tool (Simapro) was used to assess and compare different versions (prototypes) of the concept embodied and to find out the environmental impact of the product life cycle stages and components. Solidworks was also used to model and simulate the mechanical and thermal properties of the housing and the heat sink to optimise the use of materials. For example, the heat sink was modelled and simulated in order to optimise the material used in the heat sink, and the housing of the lighting product was modelled and simulated to reduce the thickness of the housing walls. More material than required is often used in many parts and components because no simulation has been carried out to check if the amount of material used is adequate for the application. Another method used was 'assessment of design features'. This method was used to assess the lighting product design features (e.g. joints, reflector, disassembly) which could be improved further in the next version (design iteration) in order to reduce the environmental impact of the lighting product. The assessment was mainly conducted by the author; however, production and marketing personnel (from the manufacturer of the lighting product) and the consumer (via structured interviews) also assessed the lighting product (prototype) and provided feedback that was used to improve it.

<u>Insights:</u>

The embodiment design stage focuses on the improvement and further definition of the final concept selected in the concept design stage. This stage is therefore a continuous process of analysis (assessment) and synthesis (design) of the final concept to define it in more detail and to reduce its environmental impact further at the same time. The role of the assessment at the end of each design iteration is to find areas (design features) that can be improved further to reduce the impact. Assessment can be conducted with LCA-based software tools or with the 'assessment of design features' method. Although LCA-based software tools can provide information about the total impact of: the lighting product, the life cycle stages, and the components, it cannot assess if the design features (joints, housing, components) can be improved to reduce the impact of the lighting product. For example, it cannot assess if the joints can be made more robust to extend the life of the lighting product. These design features cannot be assessed in this manner with LCA-based software tools such as Simapro and sustainable minds, but they affect the environmental impact of the lighting product.

Although Solidworks software was used in this stage to model and simulate the lighting product, the version used was not used the 'sustainability' version, which, in addition to model and simulate the lighting products, can also simultaneously assess the environmental impact of each design iteration implemented in the product within the same software. Although the environmental impact results provided are not very detailed, this is a very recommendable tool for product designers in the concept and embodiment design stages, because it 'links' (cause-effect) design modifications with environmental impact, providing a clear picture of how each design decision can affect the total environmental impact of the lighting product, and the environmental impact of each life cycle stage and components. The only disadvantage of this tool is that the users need to learn and design using this software, and that the LCA results are not as comprehensive and detailed as the ones produced with the LCA-based software tool Simapro. The utilisation of this type of CAD-LCA tool would avoid the use of LCA-based software tools such as Simapro every time the lighting product need to be assessed in each design iteration, which would speed and simplify the eco-design process. The environmental impact assessment with Simapro (LCA-based software tool) is very time consuming, and the time invested may not be worth the quality and accuracy of the environmental impact assessment results obtained.

4.2.4 - Detail design

During the detail design stage, prototype IV (final prototype) was defined in detail to prepare the product for manufacturing. The following sections explain the selection of the final specifications of each component (section 4.2.4.1), the technical specifications of the final prototype (section 4.2.4.2) and the versions of the final prototype (section 4.2.4.3).

4.2.4.1 - Components used in the final prototype

The final main components selected and used to make the final prototype are described below:

<u>LEDs:</u>

The final LEDs were 'Citizen CitiLED' of 6.4 W each. These were used with 2 Correlated Color Temperature (CCT): 3000 K (warm light) and 5000 K (cold light). The LEDs were compliant with RoHS directive.

<u>Driver:</u>

Two drivers were selected. The one used inside the lighting product was non-dimmable and required an integrated circuit (Fig. 4.53) to be dimmable. The other one was dimmable and was used inside walls for the version where the driver had to be integrated in the walls. Both drivers were RoHS compliant.

<u>Circuit-control unit:</u>

A circuit-control unit was designed (Fig. 4.53) for this application. This circuit-control unit controlled the driver, sensors and remote control device. This circuit could be programmed to perform several functions:

- Switch on/off and dimming by touch (touching the housing).
- Switch on/off and dimming with remote-wireless control.
- Switch on/off and dimming with conventional controls.
- Switch on/off and dimming informed by sensors (For example: When the sensor detects movement it switches on/off or dim the luminaire).

It has to be noted that in the final prototype the touch-based switch and remote control were not included to reduce the cost and environmental impact of the lighting product.

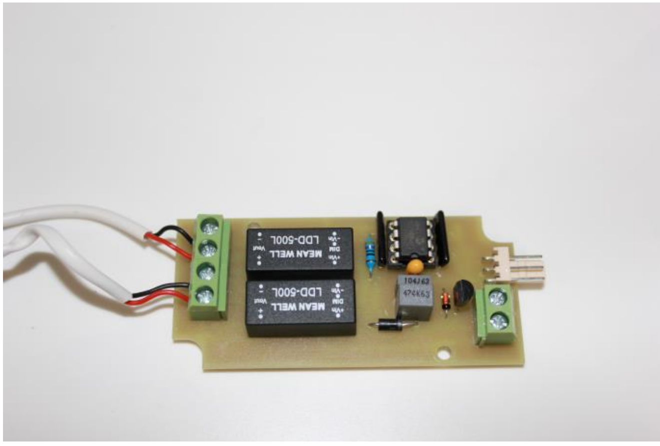


Figure 4.53. Circuit-control unit.

Heat sinks:

Heat sinks are essential components of LED-based lighting products because these are necessary to dissipate the high amount of heat produced by LEDs. High temperature is one of the main factors that shorten the LED lifespan, so heat dissipation through active or passive cooling is very important. After trying and testing, several heat sinks (as explained in previous sections) a final heat sink (Fig. 4.54) made of recycled aluminium was selected.

Figure 4.54. Heat sink bottom and top views.

Reflector:

Light reflectors and lenses (i.e. optic elements) are necessary to control the light direction. There is always light output loss when light is reflected, and this makes the luminaire less energy-efficient (less lumens/watts ratio). That is why the percentage of light reflected by the reflector had to be as high as possible. Fig. 4.55 shows the reflector-lens combination selected. This was made of PMMA and the reflector had 85% reflectivity.

Figure 4.55. Reflector-lens.

4.2.4.2 - Technical specifications of the final prototype

The technical specifications (table lamp version) are listed below. It has to be noted that each version (table lamp, ceiling lamp) can use 1-4 lighting modules. In the specifications listed below the information provided is from the lighting product with 1 and 4 lighting modules only, and it has only been explained the specifications that can influence or are related to the environmental impact of the lighting product.

- Power consumption:
  - 1 lighting module version (100% dimmer intensity): 6.7 W.
  - 4 lighting modules version (100% dimmer intensity): 24.2 W.

- Materials and finish:
  - The housings of the modules are made of 100% post-consumer recycled PET without any coating.
  - Materials, finishes and components used comply with RoHS directive.
  - Base and pole are made of recycled aluminum without any coating.

- Recycling:

  - The material used to make the housing is 100% post-consumer recycled PET, and is fully recyclable.
  - The material used to make the pole, base and heat sinks is recycled aluminum, which is fully recyclable.

- Disassembly:

  - The product can be dismantled easily and fast with snap-fit joints which do not need tools.

- Maintenance:

  - The product can be dismantled easily and fast for repair and maintenance. All the components have easy access to be repaired and/or upgraded.

- Light control (direction and intensity):

  - Lighting modules and pole can be rotated 360° to have full control of the light direction.
  - Dimmer is provided in all versions as standard to control the intensity of the light. It allowed 4 dimming settings (25%, 50%, 75% and 100%).

- Modular design:

  - This facilitates repair and upgrade. The user can add-remove 1-4 lighting modules depending on the lighting needs over time.

- Light source reliability:

- The lighting product uses reliable LEDs (Citizen brand) which has been tested thoroughly to ensure proper functioning for the period of time specified in the LED supplier specifications sheets.

- <u>Advanced features (available on request in advanced versions):</u>

  - The lighting product can incorporate occupancy and light sensors.

These specifications contribute directly or indirectly to reducing the environmental impact of the lighting product. The main design features related with the specifications that contribute to reduce the environmental impact, and how they do it are explained below:

<u>Power consumption:</u>

Power consumption affects the environmental impact caused during the use stage of the lighting product life cycle. Lighting products with lower power consumption cause less total environmental impact. This parameter is directly related with the energy-efficacy (lm/W) of the lighting product, which indicates the relationship between the energy consumed (W) and the light output produced (lm). Higher values indicate the lighting product is more energy-efficient. The final lighting product developed with 4 lighting modules has an energy efficacy of 54.54 lm/W, which is a very good value.

<u>Materials:</u>

The amount and type of materials used to make the product affect the environmental impact of different phases: Manufacturing, distribution and end of life.

In general, the smallest amount of material should be used for three reasons: 1) less materials means less extraction and manufacturing impact, 2) less material means less weight during distribution and, 3) less amount of waste at the end of life. When the amount of material has been optimised to the minimum possible, the material should be sourced from recycled (post-consumer if possible) sources, and be fully recyclable.

The materials used in the lighting product are: 100% recycled aluminium and 100% recycled (post-consumer) PET, and both are highly recyclable materials. Whilst satisfying the basic structural demands the minimum amount of materials possible has been used.

Both materials have a well-established network of collection points and recycling systems in most of the countries.

The parts made of recycled aluminium and recycled PET parts have not been coated to facilitate recycling.

Light control:

Light control is essential to save energy (and reduce environmental impact) during the use stage. In addition to having a high energy-efficacy, the lighting product should be able to provide the amount of light needed when needed, that is why the user has to be able to control the light quantity and direction in order to avoid to waste light and hence energy. This lighting product allows full directional individual control (360°) of each lighting module as well as light intensity control with a dimmer with four settings, so the amount of light needed can be used where it is required. The advanced version of the lighting product can also integrate smart controls (sensors and timers) that control when the light should be on-off depending on the information sent by the sensors, which is especially effective in public spaces where users have no agency of the lighting systems.

Modular design:

Modular design is a feature that contributes to reduce the environmental impact because it facilitates easy detachment of modules and components that need to be repaired and/or upgraded. The lighting modules of this lighting product can be attached or detached (1-4 lighting modules) depending on the user needs over time.

Components reliability:

Components' selection is very important to ensure the reliability of the system to extend its lifespan. At the detail design stage, it is key to select components from suppliers that have passed strict quality tests to ensure these will work as intended for a specific period of time under certain operating conditions.

The LEDs selected are 'Citizen-CitiLED: CLL010-0395A1-50KL1A1' which have passed strict quality standards. The driver model used is 'Eaglerise DLGE/30 W'. This driver is not a top quality driver, although it has good quality (complied with CE marking and other quality tests). However, this driver had to be selected (instead of the higher-quality Lumotec brand driver) to reduce the price of the luminaire as suggested by the consumer study and the marketing department of the manufacturer and distributor (Ona Product S.L. and Aaxsus AB). The ideal driver that should be used in this lighting product, and the one that it will be used, once the manufacturing volume increases and cost per unit can be reduced, is the 'Lumotech LEDlight 12 W mains dimmable series L05021'. This driver costs more but also has higher reliability. It has been certified by ENEC and EC, and has a 5 years' warranty and 50,000 h. estimated lifespan. As it has been pointed out in several studies (see chapter 6), the driver used in LED-based lighting products is usually one of the causes of functional failure so its lifespan and reliability should equal the LEDs used, and the whole lighting product should be pre-tested (with a burn-in-test) to avoid premature early failure.

Maintenance and recyclability:

Easy-fast disassembly and good access to components and parts is key to facilitate maintenance and hence extend the lifespan of the lighting product. Easy-fast disassembly is also important to facilitate separation of materials and recycling at the end of life.

This product can be dismantled easily and fast which facilitates maintenance and recycling, and the electronic components that may fail such as the driver, LED and circuit have easy access, and can be dismantled easily to be repaired and/or upgraded.

It has to be noted that although lighting products can be designed for easy-fast disassembly, this may not have any influence in its reparability or recyclability. For example, a lighting product can be designed to be easy and fast to dismantle, however, if the user has not specific skills (or the will to repair it) in electronics probably they will probably not be able to repair the lighting product, even when the company provides a customer service to help with this issue, and information about how to dismantle and repair the product is shown in the company website. In general, the best way to ensure that a lighting product will last for a longer period of time is by providing long warranties. Customers usually send back a failed lighting product under warranty to the company because they will receive the same product repaired, or a new one, at no cost with little effort and time invested. This strategy also benefits the company because they can re-use and recycle the components or the full lighting product again (i.e. they have control over the product). At the same time, customers do not have to care about where to dispose the lighting product to be recycled.

Similarly, a product that has been designed to be easy-fast to dismantle manually does not mean that the product has more chances to be recycled, because in the best case scenario, (i.e. when lighting products are disposed in recycling collection points) recyclers may not necessarily dismantle manually the luminaire for recycling. For example, small lighting products, with little amounts (weight) of valuable materials may not be worth to dismantle manually for a recycling company because the labour-time of staff cost more than the value than can be obtained from recycling the materials contained in the lighting product. Often, this type of lighting product is not disassembled manually, instead these are shredded directly. In this case, any effort to design a lighting product that is easy to disassembly manually will not have any influence in the recycling potential of the lighting product.

<u>Sensors:</u>

In general, the use stage is the lighting product life cycle stage with the highest impact by far, so one of the best ways to reduce the environmental impact of lighting products is focusing on the reduction of the impact produced at this stage, which is determined by the power consumption and maintenance of the lighting product. Designing an energy-efficient lighting product is, therefore, the first step toward reducing energy use and hence the environmental impact. This is achieved when the lighting product produces a high light output with a low power consumption. However, an energy-efficient lighting product can reduce its impact further if the lighting product is only functioning when is needed, and this is not always the case. For example, an energy-efficient lighting product that is on when there is no one using the room, is wasting energy and increasing its environmental impact. In order to avoid this, smart lighting controls (i.e. sensors, timers) are used. These smart controls can detect people in the room and switch on accordingly, or switch on at certain times based on a timer, among other functions.

This lighting product has been designed so it can adopt smart lighting controls, but these are only used in advanced versions, because these advanced controls increase the price. Although smart lighting controls can cause substantial energy savings, the application of these is feasible in public environments, rather than domestic environments, where users usually wish to have full control of the lighting product, so it does not make sense to provide all versions with smart lighting controls and increase the price, when these are only useful or needed for certain types of users and applications.

4.2.4.3 - Final prototype and versions

The final prototype is shown in fig. 4.56-4.58. It was developed and prototyped in two versions (table lamp and ceiling lamp) and could adopt 1-4 lighting modules. Fig. 4.56-4.57 shows the table lamp version, and fig.4.58 shows the ceiling lamp version. Fig. 4.56 (left image) shows the table lamp version with two lighting modules and fig. 4.56 (right image) with three lighting modules.

Figure 4.56. Final prototype: table lamp version, with two lighting modules (left image), and three lighting modules (right image).

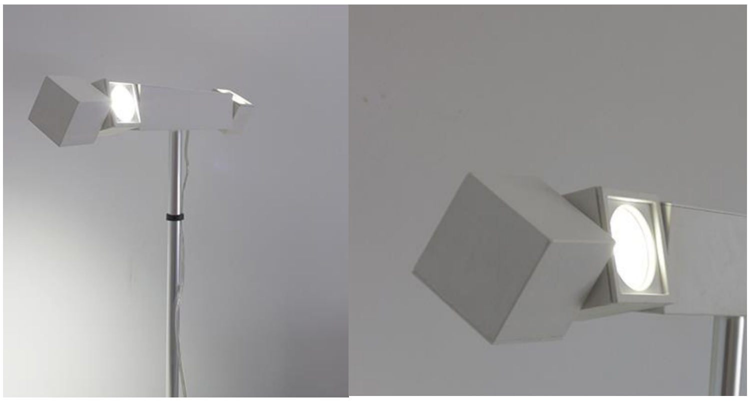


Figure 4.57. Final prototype: table lamp version, with three lighting modules (left image). Detail of full rotation of lighting modules (right image).

Figure 4.58. Final prototype: ceiling lamp version, with one lighting module (left image). Final prototype: ceiling lamp version, with two lighting modules (right image).

4.2.4.4 - Analysis and summary of insights

This section examines the tools and methods used during the detail design stage of the design process, how these were used, and which insights were gained after the use of these by the author in the case study. At this stage of the process all the components that have to be used are known, because they were defined in the embodiment stage, but it is at this stage when all the specifications (quality and type) of components, materials, and finishes are specified, included the interfaces (e.g. connections-joints tolerances) between the components. Additional versions of the lighting product for other applications (e.g. ceiling lamp) were also defined at this stage.

Tools and methods used:

At this stage generic eco-design guidelines were utilized, eco-design guidelines from the RoHS directive, and the LED driver selector on-line web-based application.

How the tools and methods were used:

Generic eco-design guidelines were used to specify the quality (i.e. type) of the components and finish used in the parts. For example, eco-design guidelines recommended to source components from well-known suppliers to ensure steady supply over time, and components that had passed reliability and quality certifications (e.g. ENEC and CE certifications) and Ingress Protection (IP) tests to increase the durability of the lighting product. Eco-design guidelines from RoHS directives were also used to ensure all the electronic components complied with RoHS directive. In addition, eco-design guidelines also recommended to select LEDs with high-efficacy and long useful life, and efficient electronic dimmable drivers (i.e. with high power factor) and long useful life (at least the same as the LED), in order to make the product more energy-efficient and long lasting. Other eco-design guidelines that were used recommended: not to use coatings on components and housings to facilitate recycling, the selection of drivers with a high IP (IP45) value to avoid the ingress of water, moisture and dust to extend the lifespan of the lighting product, and the selection of reflectors with high reflectivity ratios. The LED driver selector on-line web-based application was also used, to find the optimum match between LED and electronic driver, in order to save make the LED-driver system more energy-efficient.

Insights:

At the detail design stage, the core architecture of the lighting product has been defined already, and the role of the eco-design guidelines (generic and from directives) is to ensure that the parts and components final specifications contribute to reduce the environmental impact of the product. At this stage it has to be decided what type of final component, finish or tolerance has to be selected and eco-design guidelines can support this.

4.2.5 - Testing and certification

This section describes the testing, analysis and certifications conducted in the final prototype. The following analysis and tests were conducted: Light analysis (section 4.2.5.1), thermal test (section 4.2.5.2) and burn-in test (section 4.2.5.3). In addition, the lighting product was certified with the CE mark (section 4.2.5.4).

4.2.5.1 - Light analysis - test

A light analysis was conducted to analyse and test the light performance of the lighting product. This test analysed the quantity and quality of the light produced, and the power consumption. This information was required to conduct the final environmental impact assessment (explained in chapter 5) and obtain the technical specifications (i.e. light performance) of the lighting product to inform consumers.

The light analysis test was conducted with a table lamp version with three lighting modules at 100% dimmer intensity.

The following parameters were obtained after the test:

- Light distribution: See polar diagram (Fig.4.59-left image).
- Luminous Flux: 948 lm
- Lighting product efficacy: 55.11 lm/W

- Power consumption: 17.2 W
- Light Output Ratio (LOR): 0.95
- Color Correlated Temperature (CCT): 5000 K
- Color Render Index (CRI): 65
- Luminous flux of light source: 330 Lm (1 LED module).
- Light source efficacy: 49.25 lm/W
- Light source useful lifetime: 50,000 h.

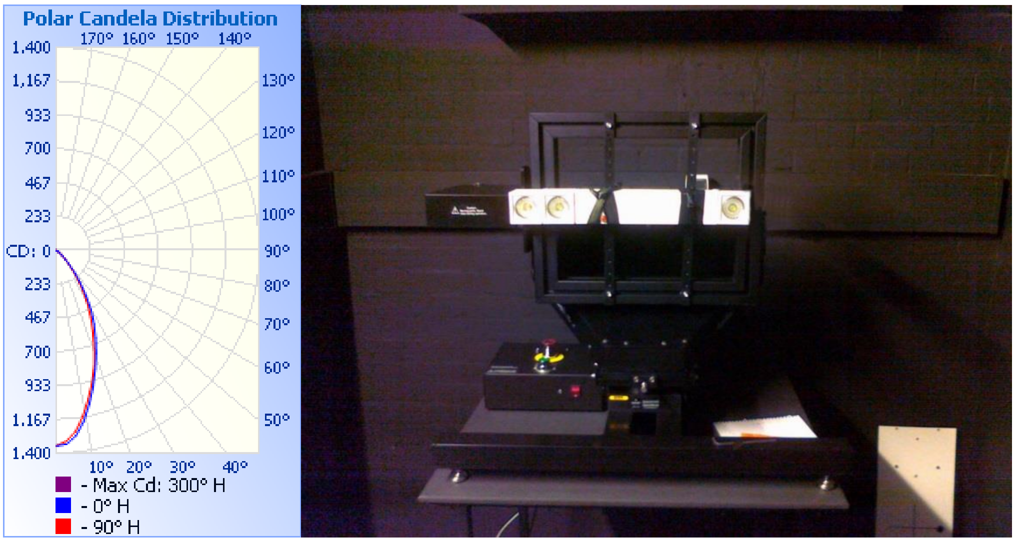


Figure 4.59. Light intensity distribution polar diagram of the lighting product (left image). Lighting product with three lighting modules mounted on the goniometer (right image).

The reason why it is necessary to conduct a test and analysis of the lighting product, is because is essential to know the light parameters of the lighting product. Some of these parameters: luminous flux (lm), power consumption (W), Colour Correlated Temperature (CCT) and light distribution, are all directly related with the environmental impact of the lighting product. For example, if we know these parameters, we can obtain the luminous efficacy of the lighting product (lm/W), its Light Output Ratio (LOR), its power consumption and the light distribution. The light distribution is necessary in order to use the lighting product efficiently. Often, light is wasted because architects and interior designers do not know how the lighting product distributes the light in the space. If the light distribution is known, then, it is possible to use the light more efficiently and save light (and energy). This analysis is also necessary to inform the final environmental impact assessment (with an LCA) of the final lighting product (explained in chapter 5).

Please see Appendix 4.3 to see the complete report results of the distribution of light analysis of the lighting product.

To conduct the light analysis and test several tools were used: Goniometer, illuminance meter, Colorimeter, power meter and several software tools: ProSource (Radiant Vision Systems, 2015a) and Photometrics Pro (JSolutions Inc, 2003). The results of the analysis of the Light sources (LEDs) were obtained assessing the light sources following: IES-LM-80-08 (IES, 2008b) and TM-21-11 (IES, 2011a) standards by the LED suppliers. To analyse the light performance of the whole luminaire, IES-LM-79-08 (IES, 2008a) standards were followed.

Explained below are each of the tools used and the function of each of these in the light analysis conducted:

Software-based analysis tools:

ProSource (Radiant Vision Systems, 2015a): This software can process the data (light) captured by the goniometer, and translate it into EULUMDAT and IES photometric files that can be exported and analysed in Photometric analysis and CAD software. The light performance of the lighting product was examined to obtain the photometric files. Photometric files ultimately provide the light distribution, luminous flux and power consumption of the lighting product, which can help to understand the lighting product performance in order to reduce its environmental impact.

Photometrics Pro (JSolutions Inc, 2003): This software can analyse the data contained in EULUMDAT and IES photometric files, and translate it into graphs-results which shows the light performance (light distribution, light intensity, beam angle) of the lighting product. After using the goniometer and ProSource software to obtain the EULUMDAT and IES files, these were exported to Photometrics Pro to analyse the light parameters and performance of the lighting product.

Hardware-based measurement tools:

Goniometer (Radiant Vision Systems, 2015b): This tool was used to capture and measure the photometric data (light) from the lighting product. The light distribution was obtained using the goniometer, and photometric files (EULUMDAT and IES) produced using ProSource software.

Illuminance meter (Konica Minolta, 2015a): This tool was used to measure the illuminance of the lighting product in lux. This value is necessary to complete the analysis with the goniometer and obtain the photometric files. The illuminance was calculated when the lighting product was mounted on the goniometer (Fig. 4.59-right image) previous to conducting the analysis with the goniometer.

Colorimeter (Konica Minolta, 2015b): This tool was used to measure the Correlated Colour Temperature (CCT) in K of the lighting product. CCT measurements are required because the colour temperature of the lighting product may differ from the one provided by the light source supplier when the light source is used within the lighting product. The lighting product function is to provide a specific quantity and quality of light, because both parameters affect the energy used and the lifespan of the lighting product. For example, if the CCT (a parameter related with light quality) degrades below certain levels, the function of the lighting product may not satisfy the user needs and hence the lighting product will be disposed and end its life.

Power meter (Maplin, 2015): This tool was used to measure the power consumption of the lighting product. The power consumption was measured before the light analysis conducted with the goniometer. The measurement was taken after 30 minutes of functioning in order to allow the lighting product to stabilise.

4.2.5.2 - Thermal - test

The thermal resistance test consisted of measuring the temperature inside the housing that contained the driver (driver module) and the housing containing the LEDs (lighting module), with a digital voltmeter and thermocouple adapter (Fluke 180 series), to confirm the heat-resistance of the housing material (PET), and the lighting product electronic components (LEDs and driver) inside the housings. The thermocouple adapter sensors were placed inside the housing that contained the driver (driver module) and the housing containing the LEDs (lighting module), and readings were taken every hour for a period of seven hours.

At the end of the test, the results (Figure 4.60) showed the maximum temperature registered inside the driver module was 34.6 °C, and inside the lighting module was 95.6 °C. Both were well below the PET material melting point temperature (250 °C) (Ashby and Johnson, 2010), and the recommended functional temperature of LEDs junctions 125 °C (Chwan, 2012), so it was confirmed that the housing and components would not suffer any fast deterioration or failure inside the lighting product.

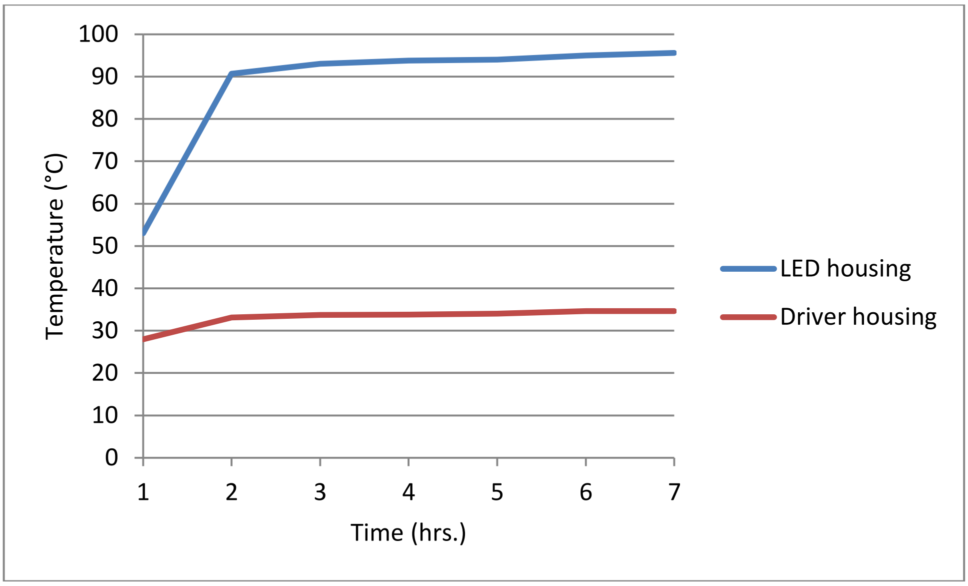


Figure 4.60. Temperature inside the lighting and driver modules (housing) over time.

Although the thermal behaviour of the lighting product can be simulated in Solidworks virtually, actual physical testing should be conducted because this is the best manner to understand how the lighting product will behave thermally in real operating conditions. If this test would have shown temperatures above 125°C or the PET material had shown signs of degradation that could affect its mechanical and optical properties, the lighting product would have to be re-designed again. This test has to be conducted to increase the reliability of the lighting product, and hence its lifespan.

4.2.5.3 - Burn-in test

The aim of the burn-in test was to detect faulty components and systems which could lead to: 1) premature failure of the lighting product, or 2) premature degradation of components leading to lower performance of the lighting product. The test consisted of switching on the lighting product for 2,000 h. non-stop to confirm it worked with the expected performance during 2,000 h. Faulty components usually fail or show anomalies within the first 1,000 h of functioning, that is why, burn-in tests should last, at least, 1,000 h., according to the Next Generation Lighting Industry (Next generation Lighting Industry, 2014). The reason why burn-in tests should always be included in the eco-design process of lighting products is because LED-based lighting products do not always last ~50,000 h as reported by manufacturers or suppliers. Field studies conducted by US DOE (US DOE, 2009b) revealed that some LED-based lighting products were beginning to fail after 1,000 h. The ones that failed prematurely, presumably, had faulty components and systems that would have been detected by burn-in tests.

4.2.5.4 - CE mark - certification

The CE mark is required for products that have to commercialised in the EU market. It involves a series of tests following specific standards regarding safety. Although the purpose of this test is to comply with EU regulations, this certification also ensures a minimum set of quality standards that can increase the reliability and safety of the lighting product, therefore contributing to extend its lifespan and increase the well-being (Safety) of the end user.

The CE mark for LED-based lighting products comprises a number of tests following these standards:

- BS EN 60598-1:2008: Luminaires. General requirements and tests (BSI, 2008d)
- BS EN 60598-2-1:1989: Luminaires. Particular requirements. Specification for fixed general purpose luminaires (BSI, 1989).
- BS EN 60598-2-6:1995: Luminaires. Particular requirements. Specification for Luminaires with built-in transformers or convertors for filament lamps (BSI, 1995).
- BS EN 62031:2008+A2:2015: LED modules for general lighting. Safety specifications (BSI, 2008a).
- BS EN 62471:2008: Photobiological safety of lamps and lamp systems (BSI, 2008b)
- BS EN 61347-1:2001+A1:2008: Lamp control gear. General and safety requirements (BSI, 2001b).
- BS EN 61347-2-13:2006: Lamp control gear. Particular requirements for d.c. or a.c. supplied electronic control gear for LED modules (BSI, 2006a).
- BS EN 55015:2001: Limits and methods of measurement of radio disturbance characteristics of electrical lighting and similar equipment (BSI, 2001a).

- BS EN 61000-3-2:2006+A2:2009: Electromagnetic compatibility (EMC). Limits for harmonic current emissions (equipment input current ⩽ 16 A per phase) (BSI, 2006b).
- BS EN 61000-3-3:2008: Electromagnetic compatibility (EMC). Limits. Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current ⩽ 16 A per phase and not subject to conditional connection (BSI, 2008e).
- BS EN 61547:2009: Equipment for general lighting purposes. EMC immunity requirements (BSI, 2008c).

4.2.5.4.1 - Design changes after first CE test

After the first trial to pass the CE mark tests (European Commission, 2015b), the testing lab informed that some design changes had to be implemented in the lighting product in order to pass the tests. Explained below are the two main problems found during the test and how they were solved:

Electronic connector between lighting modules:

The connector that attached the LEDs cables of one LED inside a lighting module to another LED of another lighting module needed to have a very small size in order to be able to pass through the small hole in the lighting module housing that communicates all the modules-housings. The connectors that passed the CE tests had a large size so they did not pass through the hole, and the available connectors with small size did not pass the safety certifications of the CE mark. Finally, a standard connector of very small size (Fig. 4.61) was found and tested successfully.

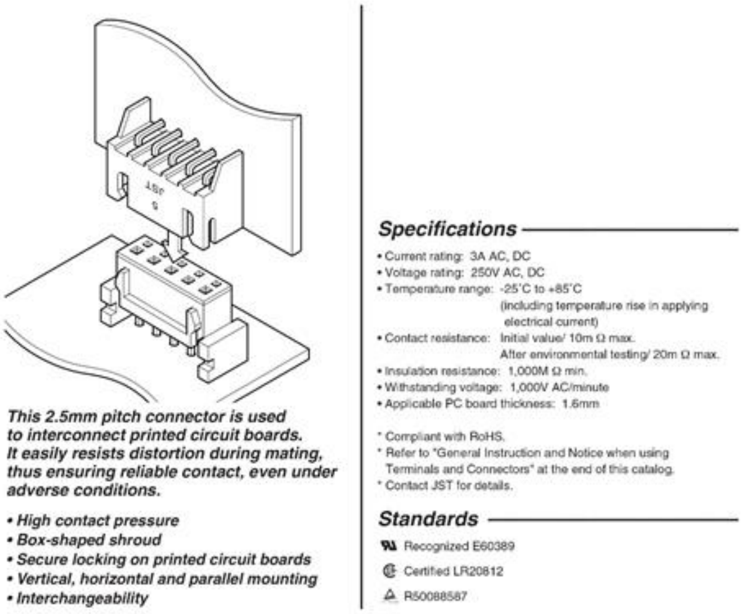


Figure 4.61. connector used to connect the cables between lighting modules.

Joint-connector between modules:

The initial snap-fit joint-connector used to join the modules (Fig. 4.62-left image) facilitated easy-fast disassembly. The lighting product was so easy to disassembly that the modules could be dismantled using one single hand without the need of tools. Initially, this was supposed to be a success (it was extremely easy to dismantle), but it turned out that it did not pass the safety tests. Thus, the joint-connector had to be re-designed several times to allow easy disassembly (without tools), whilst being able to pass the CE safety tests. A new joint (Fig. 4.62-right image) was designed that allowed easy disassembly, whilst being well enough attached to pass the safety tests.

The new snap-fit joint-connector was designed specifically for this application (non-standard joint) and it was made of the same material used in the housing (100% recycled PET) to facilitate recycling.

Figure 4.62. Initial joint selected to join the modules (left image). Final joint designed to join the modules (right image).

Joint-connector between modules and rotation:

In order to have full control of the light direction, the lighting modules had to allow full rotation (360°). The initial snap-fit joint-connector used (Fig. 4.63-left image) could be rotated more than 360°, because it had no limit at the end of the full rotation, which might cause the breakage of the wires. This was one of the reasons why it did not pass the safety tests. The new designed final snap-fit joint-connector used (Fig. 4.63-right image) allowed a maximum rotation of 360°, thus avoiding to break the wires.

The CE mark tests, like other type of quality tests, are beneficial from an eco-design point of view because increase the reliability (durability) of the lighting product and also can enhance the well-being (safety) of the end user.

4.2.5.5 - IP44 - certification

The lighting product had to pass IP44 (IEC, 2015c) tests in order to reduce the possibility of components' failure due to external environmental effects (i.e. moisture, water, etc.). This test increased the reliability of the lighting product, and hence its lifespan. This test was also necessary to widen the scope of market niche and applications (i.e. use in toilets or terraces). This certification is required when the lighting product's intended use is not in very exposed outdoor environments and/or in humid indoor atmospheres such as toilets.

In the IP code nomenclature, the first digit indicates the level of protection against access to hazardous parts and the ingress of solid foreign objects, and the second digit indicates the level of protection that the enclosure provides against ingress of water. In this case, the level of protection against hazardous parts or solid objects is 4, which means that the lighting product is protected against particles of >1 mm., and the level of protection against ingress of water is 4, which means that the lighting product is safeguarded against splashing of water.

The following test was conducted: *Full test type: STEP AIR + IP44*

4.2.5.6 - Other certifications and labels considered

The ENEC mark (EEPCA, 2015) is a high-quality certification that ensures the lighting product complies with rigorous quality and safety standards. This mark does not only evaluate the product itself, but also the manufacturing processes used to produce it. Initially, the ENEC mark was considered to improve the reliability of the product and to communicate the quality of the lighting product to consumers. However, the marketing department of Aaxsus AB, involved in the distribution of the lighting product, informed that this certification was not demanded by consumers usually, and considering the high cost of the certification it was not implemented, as it would have increased the total cost of the lighting product.

The ‘Energy Star’ label (EPA, 2015) is the only eco-label that covers lighting products, but currently this label only applies to lighting products marketed in USA. It takes into account the energy efficiency, durability and light control of the lighting product. Since it is not available for luminaires marketed in the EU, it was not taken into account in the design process.

At the time this research was conducted, there was no eco-label applicable for lighting products marketed in Europe, although a new eco-label for lighting products could be created soon following an EU-funded project (Ecolighting, 2015) that is working on this issue. The current EU eco-label (European Commission, 2015c) do not have any product group-category with criteria suitable for lighting products at the moment. This means that the only manner to provide information about the environmental credentials of the product to the consumer is through an Environmental Product Declaration (EPD). In order to produce an EPD (EPD International AB, 2015), it is necessary that the product is assessed with a Life Cycle Assessment (LCA).
In this research, a LCA-based environmental impact assessment of the final prototype was conducted (chapter 5), however the results were not verified by a third party, which is required in order to produce an EPD. Nevertheless, the results of the LCA could be verified in future work to obtain an EPD. In absence of an eco-label for lighting products, this is the best option to provide information about the environmental credentials of the lighting product. EPD information can also be used to compare (eco-benchmark) different products by consumers, provided the other products also provide EPD-related information. Two of

the largest problems with eco-labelling are: 1) the environmental information provided cannot be understood (it is not meaningful) by the consumer, and 2) there is not a worldwide single compulsory reliable standard created to facilitate comparison, which means that sometimes different products have different eco-labels, and they cannot be compared.

4.2.5.7 - Analysis and summary of insights

This section examines the tools and methods used during the testing and certification stage of the design process, how these were used, and which insights were gained after the use of these by the author (product developer) in the case study.

Tools and methods used:

At this stage the following tests were utilised: Light analysis test, thermal test, burn-in test, IP44 test, and test to obtain the CE mark. Different tools and methods were used in each test. In the light analysis test the following tools were used: goniometer, illuminance meter, colorimeter, power meter, and the software tools: ProSource and Photometrics Pro. In the thermal test a digital voltmeter and thermocouple adapter were used, and in the IP44 test an IP test chamber was used. During all the tests several methods and standards were followed as it has been explained previously.

How the tools and methods were used:

The tests were conducted consecutively in this order: 1) Thermal test, 2) CE test 3) IP44 test, 4) Burn-in test, 5) Light analysis test. The thermal test was conducted to ensure that the temperature inside the housings of the driver and the lighting modules was below the allowed thresholds that could damage the housing material and electronic components, thus reducing the end of life of the product. The CE test was performed because it is compulsory for lighting products that have to be marketed in the EU. However, this test also increases the durability and safety of the lighting product. The IP44 test was conducted to ensure the product was well sealed. This has several benefits: first it allows the lighting product to be used in toilets and other outdoor applications. Second, it ensures the electronic components inside will not be affected by external environmental factors (e.g. moisture, water, dust) which can reduce the lifespan of the product or even led to catastrophic failure. Once all the previous tests had been passed after the re-design of some parts, the lighting product was subjected to a burn-in test to reveal any manufacturing fault in the components and/or a bad design of any sub-system. After the final lighting product had been re-designed to pass all the tests and certifications, the light analysis test was conducted to obtain the parameters (luminous flux, power consumption) related with the performance of the lighting product to inform the final environmental impact assessment using a LCA-based software tool Simapro (explained in chapter 5), to test the proper functioning of the product, and to inform consumers.

Insights:

All the tests and certifications (except the light analysis test) utilised at this stage of the design can be considered eco-design tools, because they contribute to increase the reliability and durability of the lighting product, and therefore its lifespan. The light analysis test also contributes to reduce the environmental impact of the lighting product, by providing information about the lighting product performance (e.g. luminous flux, power consumption) which is necessary to inform robust environmental impact assessments (through LCA-based software tools), which are essential to obtain EPD and Eco-labels to advise consumers. Information about the distribution of the light is also needed by professionals who design installations and spaces (i.e. architects and interior designers) with lighting products. These professionals need to know the light performance of the lighting product they use in their designs so they can match the lighting product performance with the lighting needs of the space they design. Light is often wasted because there is no information about the light performance of the lighting product. This information is provided in EULUMDAT/IES photometric files, which contains all the photometric data about the lighting products. These files are obtained in the light analysis test, and can be exported to different CAD and Light design software such as DIAlux (DIAlux, 2015). Tests are often used in non-eco design processes too in order to enhance the quality of the products, but these can greatly increase the durability of the lighting products making them essential in eco-design processes. One of the drawbacks of tests is that they are time-consuming and expensive, thus extending the duration of the design process and the cost of the product. In large companies some of these tests are conducted in-house, but in small companies these tests and certifications are usually outsourced.

During this stage it became clear how safety regulations can be a barrier to develop eco-design lighting products in some occasions. For example, in the case study, the lighting product was designed to be extremely easy to dismantle (following eco-design guidelines), however this did not allow the lighting product to pass the CE mark-safety tests, due to be considered unsafe for users to dismantle a product that conduct current so easily.

It has been observed that an eco-label for (LED) lighting products would facilitate the consumer to identify and compare eco-lighting products and their environmental credentials.

4.3 - Case study: Packaging of LED-based lighting product

In this section it is described the design process of the packaging of the LED-based lighting product. It begins by explaining the PDS (section 4.3.1), followed by the concept design (section 4.3.2) and embodiment design (section 4.3.3). The design process of the packaging is not as extensive and detailed as the LED-based lighting product, but it has also been explained in this research because eco-design usually takes a life cycle approach and all the life cycle stages (including packaging and distribution) should be considered.

4.3.1 - Product Design Specifications (PDS)

The design process of the packaging began with the packaging specifications. Only the eco-design specifications have been included. These have been mainly informed by eco-design guidelines related with packaging:

<u>Eco-design guidelines – packaging:</u>

- Use as few materials as possible.
- Use recycled and recyclable materials.
- Use one or a few types of materials in the same product.
- Avoid the use of banned toxic materials (based on RoHS).

- Use materials which have established recycling networks.
- When selecting recycled materials select post-consumer recycled materials.
- Avoid the use of adhesives and glues.
- Use light (low density) materials.
- If using more than one material, they should be compatible for recycling.
- Avoid the use of packaging if possible.
- Design packaging with minimum weight and volume.
- Design packaging to be re-used and recycled.
- Avoid solvent-based inks in printed areas.
- Use the required packaging for protection only (not over package).
- Avoid the use of labels, use emboss to mark components.
- Facilitate reuse and recycling by using standard codes for identification (labelling) of materials and components.

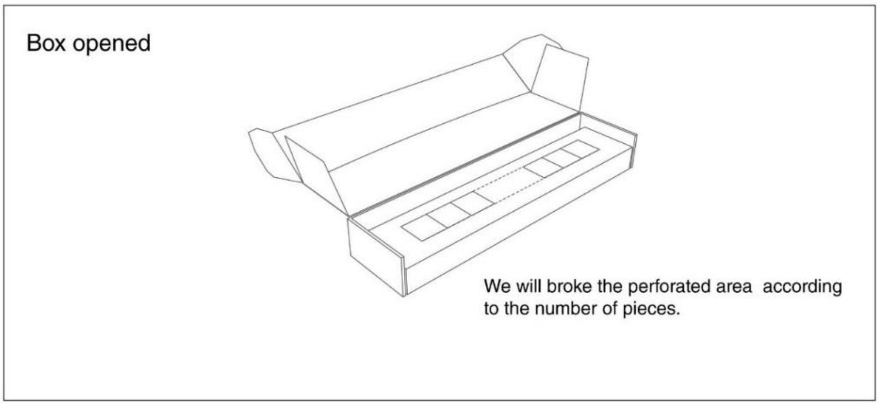
Eco-design guidelines – regulations directives:

The Packaging and Packaging waste directive (European Commission, 1994):

The main objective of this directive is to reduce packaging material excess, to eliminate and avoid specific hazardous substances and materials, inform the consumers about the material content of product and packaging, reduce the amount of waste at end of life of the packaging, in-crease and promote re-use and recycle of packaging waste and translate to the manufacturer the responsibility to recuperate and recycle its packaging. This directive is not specific to lighting products only, and affects any type of product that uses any type (primary and/or secondary) of packaging.

4.3.2 - Concept design

The packaging was designed (Fig. 4.63) based on the PDS (section 4.3.1). The material used in the packaging was 100% recycled (post-consumer) corrugated fibreboard, which is a highly recyclable material. Only one material was used for the whole packaging to facilitate recycling. The minimum amount of material was used whilst keeping the minimum structural requirements to protect the product during distribution. The design featured a modular design, which means that one single type of packaging could be used to package different versions (with 1-4 lighting modules). The packaging could be assembled without glue or any additional joint, and did not use any banned compound specified in RoHS directive. It had no finish (coating) or lamination in order to facilitate recycling.



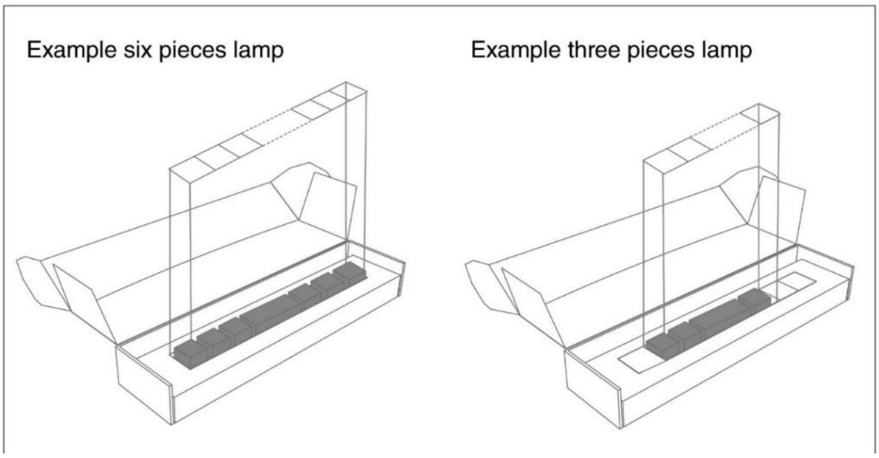


Fig. 4.63. Concept design of the packaging.

4.3.3 - Embodiment design

Several prototypes (prototypes I and II) were made based on the concept.

In prototype I the structure of the packaging was studied (Fig. 4.64), and in prototype II (Fig. 4.65) the information to be displayed on the packaging.

Figure 4.64. Packaging (Prototype I).

Fig. 4.64 shows the details of the perforated lines on the corrugated fibreboard layer inside the packaging that allows to package different versions (with different amount of lighting modules: 1-4) of the lighting product. For example, if the lighting product to be packaged has three lighting modules, then three ‘squares’ with perforated lines have to be pressed to create three ‘gaps’ to fit in the lighting modules.

In addition to providing protection to the lighting product during the distribution process, the packaging also has to offer information to the consumer (and logistic operator, in some cases) before and after purchase. Initially, printed text was selected (Fig. 4.65-left image), however, inks usually contain heavy metals and solvents, and should be avoided if possible, so it was decided to perforate the corrugated fibreboard to provide the information in order to avoid inks (Fig. 4.65-right image). This is a good solution since no additional materials or substances are used, so the whole packaging uses one single material which facilitates recycling.

Figure 4.65. Packaging (Prototype II) of the luminaire with ink-based printed information (left image) and perforated-based information (right image).

Inside the packaging, an A5 sheet made of recycled paper was included (Fig. 4.66) with information about: Assembly instructions, warranty conditions, and company contact details. It was considered to provide this information on-line (in the company website), instead of on paper, to reduce the environmental impact produced to produce the A5 printed sheet. However, the manufacturer suggested that consumers often do not have internet access when they have to assemble the product, or they may not have time to look for this information in the company website. This is especially the case with installers (i.e. in hotels). For this reason, the information was provided on-line in the company website, and also in the A5 sheet which was placed inside the packaging.

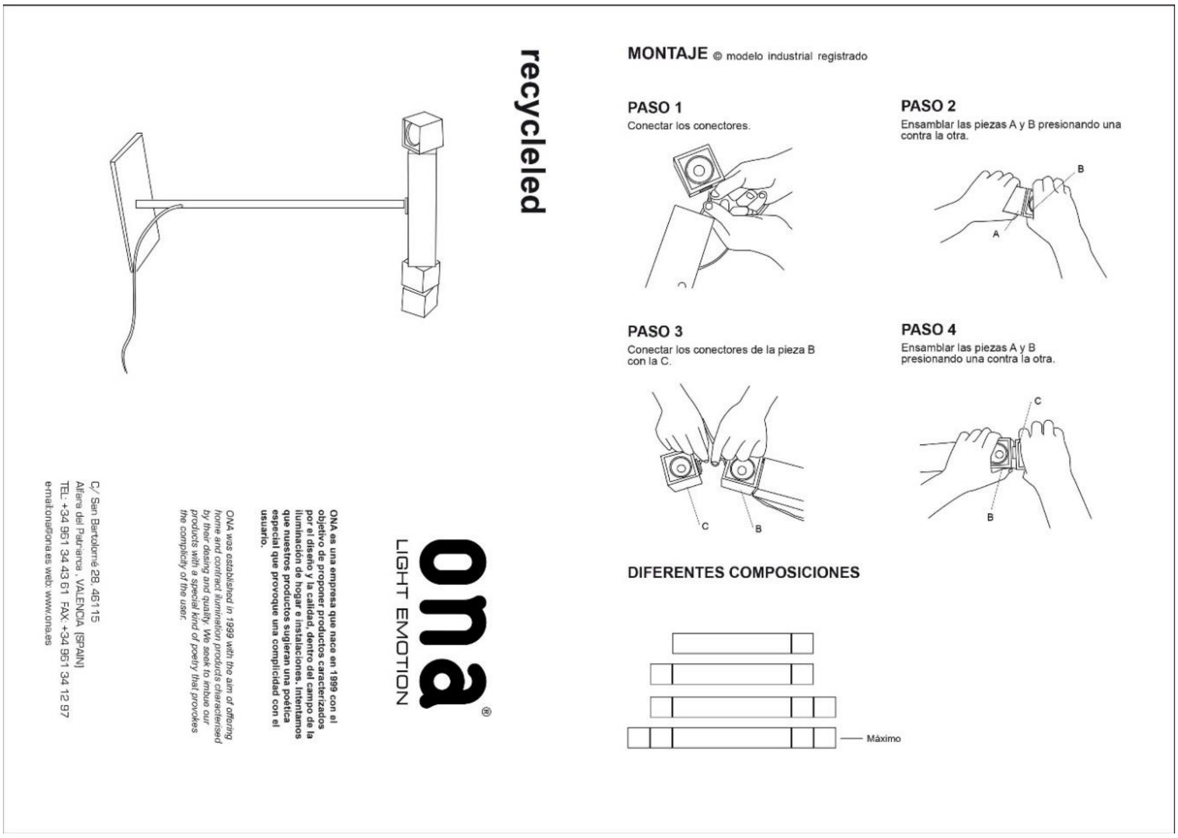


Figure 4.66. Information sheet included inside the packaging.

This sheet could also contain information about other issues such as the certifications and labels the lighting product has passed and obtained, and also about what to do when the lighting product fails or how and where to dispose it at the end of life. All this information is already provided in the company website.

4.3.4 - Analysis and summary of insights

This section examines the tools and methods used during the packaging design stage of the design process, how these were used, and which insights were gained after the use of these by the author in the case study.

Tools and methods used:

During the design of the packaging it was used eco-design guidelines (generic, and from directives).

How the tools and methods were used:

The Eco-design guidelines were used to inform the PDS, and as a checklist to ensure that these were taken into account in every design iteration until the last version of the packaging was designed.

Insights:

The final result of the eco-packaging shows that only using eco-design guidelines can be enough to design a packaging with low environmental impact when there are time and resources constraints. If time had allowed, the next step would have been to conduct an environmental impact assessment (with LCA-based software tools) of the packaging to see which life cycle stages and parts had the highest impact in order to continue the design process further focusing on reducing the impact in those areas through eco-design strategies. Since the product life cycle stage with the highest impact in the packaging is usually the manufacturing stage, it is recommendable to focus on reducing the amount of material and manufacturing processes used as much as possible, because these are the main issues that affect the environmental impact in the manufacturing stage. Nearly all the eco-design guidelines applicable to generic products can also be applied to the packaging, in addition to the eco-design guidelines specific for packaging. If time allows, the same eco-design process (in terms of depth) followed with the main product should be conducted with the packaging, because the packaging can be considered a product in itself. One key aspect in the eco-design of packaging is the weight and volume, this is particularly important because it affect the impact in the distribution stage, because more volume and higher weight of packaging usually means higher impact. As a general rule, any type of packaging should be avoided if this is possible. One of the insights gained is that consumers (especially installers) need the information sheet provided inside the packaging with instructions about assembly and other specifications of the lighting product. Initially, it was decided to provide the website name only so they could check via on-line all the information, with the final aim to avoid to use additional material (paper) and manufacturing processes (printing, cutting). However, the manufacturer clearly stated that installers and other consumers demanded to have hardcopy-based information at hand when they received the product, because many times they could not have internet access or had the time to search in internet. The lesson learnt is that eco-design strategies cannot be implemented before checking with the final end user if this will be suitable for their needs. Many times, eco-product designers implement eco-design strategies that reduce the environmental impact of the products, but sometimes these do not suit the end user needs, which means that products are not purchased and other non-eco products are bought instead, or worse, that eco-products are purchased and replaced soon after by other products that suit the customer needs. Price and convenience should also be considered in addition to the green credentials of the product, and this can be achieved by conducting consumer studies as it was shown in the concept design (section 4.2.2) and embodiment design (section 4.2.3) sections of this case study.

4.4 - Case study: System designed around the lighting product

A system has been designed and implanted in the company policy to: 1) Extend the lifespan of the lighting product, and 2) Facilitate and encourage the re-use and recycling of the materials used in the lighting product to contribute to a circular economy.

4.4.1 - Repair, re-use and recycling system

The aim of the system (Fig. 4.67) was to extend the lifespan of lighting products by facilitating and encouraging the repair, re-use and recycling of the materials utilised in the lighting product. This system was implemented in the policy of Ona Product S.L. as far as it was economically viable.

The possible routes or scenarios followed by the lighting product once is manufactured, and how the system contributes to extend the lifespan of the product and its repair, re-use and recycling in each of these routes or scenarios is explained below.

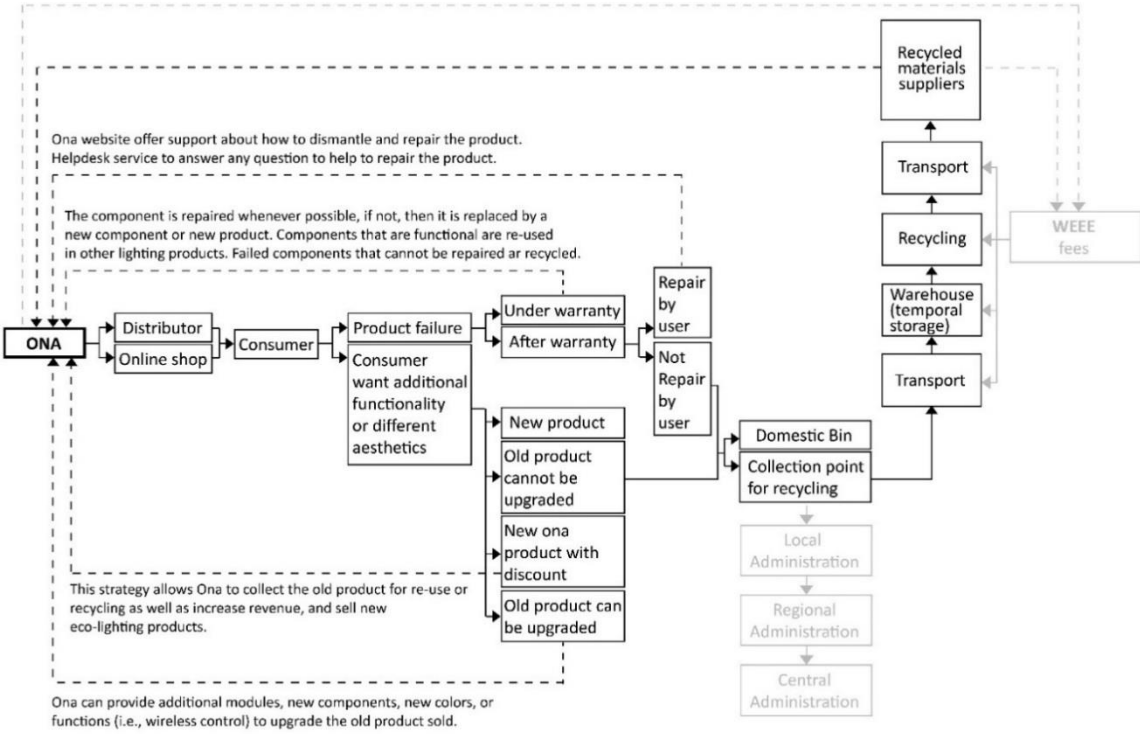


Figure 4.67. Repair, re-use and recycle system diagram.

The company commercialises the lighting product via on-line shop or via distributor (shops). When the lighting product is commercialised on-line, it is sent to the consumer directly, and when the luminaire is commercialised via distributor, the luminaire is sent to the distributor, which then sells the lighting product to the consumer.

Once the lighting product has been purchased by the consumer, several scenarios can occur during the use stage of the lighting product life cycle, which may cause the end of life of the lighting product:

- Scenario A:
  The consumer wants to dispose the lighting product because it had a functional failure.

- Scenario B:
  The consumer wants to dispose the lighting product because they wish new functions and/or new aesthetics (technical or aesthetical upgrade).

The possible routes that can take the lighting product in each of these scenarios are explained below:

<u>Scenario A:</u>

It is possible that the lighting product stops functioning after a period of time for a number of reasons, if this is the case the lighting product may take different routes:

1. The lighting product that has a functional failure may be sent back to the company when it is under warranty. The company then will try to repair it (i.e. change the damaged component), or if this is not possible, a new one will be sent to the consumer. In the first case, the company can recuperate the damaged component for re-use or recycling, and in the second case, the company can recuperate the full product for re-use or recycling. If some components are in relatively good conditions, these will be re-conditioned and re-used again in other lighting products, if these are not in good conditions they will be recycled.

   The system developed provides a 5-year warranty (longer than the standard warranty), which means that, in theory, consumers will return the failed lighting products to the company to obtain a new one, and hence these will not be disposed. Long warranties are a good strategy to extend the lifespan of the products and to recover its materials.

2. If the lighting product fails when the warranty is over, then the consumer may try to repair it himself with the support of the company guidelines of how to dismantle and repair it, as well as the help contact point of the company. All this information is provided in the company website with information about references of spare parts. However, it is possible that the consumer does not have the skills, time or will to repair it, in that case the lighting product will be disposed in: a) domestic bin, or b) recycling centre. If it is disposed in the domestic bin, it will usually end up in a landfill or burned for energy recovery in the best case scenario. On the other hand, if it is taken to the recycling centre, the materials contained will be separated and recycled. In order to encourage consumers to dispose the lighting product in the

recycling centre, information about the recycling and collection points in Sweden and Spain (initially) is provided in the manufacturer's website, which explains that the lighting product is made of recyclable materials and it should be disposed in recycling centres (e.g. eco-parks).

Scenario B:

It is also possible that the lighting product functions perfectly but the consumer wishes to replace it because they need or desire an upgrade. This upgrade can be technical (i.e. new functions) or aesthetical (i.e. new colours, shapes). In this scenario the lighting product may take different routes:

1. The product can be upgraded: The company can provide functional upgrades. For example, new LEDs can be upgraded by the company at no cost, if requested by the consumer.

2. The product cannot be upgraded: The upgrade desired by the consumer cannot be provided by the company. If the product cannot be upgraded, the company can provide a new lighting product with special discount if the old one is returned. The aim of this strategy is, again, to recover the materials and components of the old product for re-use and recycling.

3. If the consumer is not interested in the new lighting products the company have in its catalogue, the consumer will buy a new lighting product from another company, and the lighting product will be disposed in: a) domestic bin or b) recycling centre.

   The purpose of the system developed is to propose solutions to extend the lighting product lifespan, and when this is not possible, to ensure its re-use or recycling by recuperating the product or by encouraging and facilitating its re-use and recycling.

4. In the case that the lighting product is disposed in a collection point or recycling centre, the WEEE scheme fees that are paid by the manufacturer to the recycling centre (Ambilamp, 2015 and El-Kretsen, 2015) covers the collection, transport and

treatment (in recycling centres) of the lighting products, which supply the recycled materials to materials suppliers, that sell the recycled material to companies that use recycled material, to manufacture new products (see fig. 4.67).

4.4.2 - Analysis and summary of insights

This section discusses the insights gained during the design and implementation of the system around the lighting product by the author in the case study.

Insights:

The system was designed to reduce further the environmental impact of the lighting product beyond the possible environmental impact reductions gained through the application of eco-design tools and methods during the eco-design process of the lighting product. One of the limitations in reducing the environmental impact of lighting products is that, manufacturers (and product designers), can only control (and reduce) the environmental impact caused by the lighting product in some product life cycle stages such as manufacturing (of product and packaging) and distribution, but they cannot control totally the environmental impact caused in other life cycle stages such as the use and end of life stages, because they cannot control how the lighting product will be used and disposed by the end user. That is why it is necessary a system that can facilitate keeping control of the fate of the lighting product once it leaves the factory. This system can create the incentives to facilitate repair, re-use and recycling of the lighting product. One of the findings regarding repair is that consumers usually do not repair the LED-based lighting products. The manufacturer (Ona Product S.L.) stated that when LED-based lighting products fail, they call the company to have them repaired, and if it the company cannot repair them these are disposed. It is assumed that they do not repair their products because they do not have the skills or the time to do it, and although this is facilitated with information in the website about how to dismantle the lighting product and where to find spare components (i.e. ref. components is provided), they still do not know or wish to repair their lighting products. A clear incentive to avoid this is through long warranties. These provide an incentive to return the failed lighting products, which benefits the consumer (they receive a new or repaired product) and the company (they recover the materials). In other cases, consumers dispose the lighting product because they wish an upgrade (aesthetical or functional). In these cases, this behaviour cannot be controlled by the manufacturer or product designer, but it is possible to offer the possibility to upgrade the lighting product by the manufacturer, or provide discounts in exchange of the old lighting product to purchase a new one. It is also necessary to provide incentives to recycle the lighting product, and this can be facilitated by providing information about how to dismantle the product and where to recycle it, but ultimately it is the consumer who will decide where the lighting product will be disposed, despite the efforts of the product designer to design the lighting product for easy disassembly and recycling. In this area, there was the discovery that easy disassembly may not always contribute to increase the recycling potential of the lighting product, because lighting products are not always dismantled manually before recycling. Sometimes, they are sent directly to the shredder, when the disassembly operators' cost (staff cost) is higher than the value gained by separating manually some components or parts.

4.5 - Key issues that influence the environmental impact of LED-based lighting products

During the case study several lighting product-related key issues were discovered that influence the environmental impact of LED-based lighting products: Quantity and type of materials used, quantity and type of manufacturing processes used to shape and finish the materials, power consumption, disassembly, durability and reliability, volume, maintenance, technical and aesthetical upgrade.

Quantity/type of materials:

The amount of material used and its quality have a major influence in the total impact. The more materials used the more resources and energy used for its extraction and refinement, which means higher impact. The quality or type of material used is also key. The selection of materials affects the manufacturing lighting product life cycle stage, which is one of the stages that can be controlled totally by the manufacturer-product designer.

Quantity/type of manufacturing processes:

Materials are shaped and (sometimes) finished to produce components, which are then assembled to form parts, which are then assembled into products. All these activities need manufacturing processes. The amount of manufacturing processes used during the manufacturing of a lighting product, and the type of these will influence the environmental impact of the lighting product. The selection of manufacturing processes affects the manufacturing lighting product life cycle stage, which is one of the stages that can be controlled totally by the manufacturer-product designer.

Power consumption:

The energy used to power the lighting product during the use stage also influences the total impact of the lighting product. LED-based lighting products are energy-dependent products, and as such, the highest impact is usually allocated in the use stage, due to the energy consumed during the use of the product. This design feature (i.e. power consumption) affects the use stage of the lighting product life cycle, which is one of the stages that is not totally under the control of the manufacturer-product designer.

Disassembly:

The easiness of disassembly of a lighting product is also another issue that affect the impact. LED-based lighting products that are easy to disassembly are easier to repair, upgrade and recycle. Ease of Disassembly is determined by how easy or difficult is to dismantle a product, and how long it takes to dismantle it. This issue affects the use and end of life stages of the lighting product life cycle, which are the two stages that are not totally under the control of the manufacturer-product designer.

Durability and reliability:

The durability and reliability of a LED-based lighting product and its components affect the lifespan of the lighting product, and hence its environmental impact. Lighting products with reliable (and thoroughly tested) components and systems will be less prone to failure and hence more durable. This issue affects the use stage of the lighting product life cycle, which is one of the stages that is not totally under the control of the manufacturer-product designer.

Volume and weight:

The volume and weight of a LED-based lighting product will affect the volume needed during the distribution of the product to the consumer. Lighting products with higher volume and weight will have higher environmental impact during distribution. This issue affects the distribution stage of the lighting product life cycle, which is one of the stages under the control of the manufacturer-product designer.

Maintenance:

The maintenance of the lighting product can affect its lifespan, and hence it affects its environmental impact. Lighting products that can be repaired and maintained will last longer and will perform better during its useful life. This issue affects the use stage of the lighting product life cycle, which is one of the stages that are not totally under the control of the manufacturer-product designer.

Technical and aesthetical upgrade:

Technical and aesthetical upgrading of the lighting product can affect its lifespan, and hence it affects its environmental impact. Lighting products that can be upgraded technically (e.g. new functions), or aesthetically (e.g. new shapes, colours), will be able to evolve with the consumer changing preferences, and last longer. This issue affects the use stage of the lighting product life cycle, which is one of the stages that are not totally under the control of the manufacturer-product designer.

4.6 - Advantages and disadvantages of tools and methods applied

The advantages and disadvantages (as experienced by the author) of the tools and methods applied during the design process in the case study are listed below:

<u>Eco-design guidelines:</u>

Two types of eco-design guidelines were applied: generic, and eco-design guidelines informed by regulations and directives.

Advantages:

The advantages of eco-design guidelines are that they are easy to use and apply, flexible, cover different areas (disassembly, materials, manufacturing processes, regulations and directives), and do not require previous experience and knowledge about environmental issues. These can also be applied at any stage during the design process as checklists, to ensure that these are included as much as possible in each decision-making process (i.e. design iterations). Eco-design guidelines are especially useful at the beginning of the design process when no other eco-design tools can be used because there is no concept or prototype to be assessed yet.

Disadvantages:

The disadvantages are that they can only be used to recommend eco-design actions, but they cannot help to assess the environmental impact of a material, manufacturing process, concept or finished lighting product. In this sense, they also cannot help to compare and assess two design decisions, or to compare two design concepts or versions.

<u>LCA-based software tools and methods:</u>

Two types of LCA-based software tools were applied: Sustainable Minds and Simapro.

Advantages:

These tools can help to choose the material, manufacturing process, distribution process, or other industrial process with the lowest environmental impact. They can also be used to assess and compare design solutions (i.e. design features) and full concepts or prototypes. The results of the assessment of a full concept or prototype can provide information about: 1) total environmental impact of the product, 2) environmental impact of each life cycle stage, and 3) environmental impact of each part and component. LCA-based software tools (especially Simapro) is one the most reliable and objective tool to assess the environmental impact of a design feature or lighting product nowadays.

Disadvantages:

The problem with this type of tools is that they are difficult to use (the user need specific skills to use them), and the assessment is time consuming. In addition, the amount and detail of data required in each assessment is high, which is not always available at the early stages of the design process (i.e. concept design stage). Part of the assessment of the product is based on assumptions, and the less defined the product is, the more assumptions have to be made, which means that the results are not totally accurate or reliable. For example, the assessment needs information about how many hours the lighting product will be functioning, and how it will be disposed, and this information have to be assumed, because it is not available, even when the lighting product is totally defined (i.e. at the end of the design process). It is also important to notice the difference between different types of LCA-based software tools. Sustainable Minds is a design-focused LCA-based software tool, whilst Simapro is a LCA expert-focused tool. Whilst Sustainable Minds has an interface that is more user-friendly, and better adapted to answer product designers' needs, the results of the assessment are less accurate and the type of assessment cannot be as advanced (e.g. with end of life scenarios, and different assessment methods available) as the one conducted with Simapro. Assessments conducted with Simapro take more time, and require higher quantity and quality data, but the results are more accurate and reliable. This tool cannot be applied at the beginning of the design process when there is no lighting product (concept or prototype) to assess.

Assessment of design features:

This method, which was applied during the design process, is not presented in the literature as a method, but it was very effective.

Advantages:

The key advantage of this method is that it allows you to assess design features of the lighting product, which affect its environmental impact, but cannot be assessed and detected by an environmental impact assessment conducted with LCA-based software tools. The method is easy to apply, and can be applied in each design iteration during the embodiment design stage in order to reduce the environmental impact of the lighting product after each iteration. The only requirement is that a concept or (preferably) a functional prototype is needed in order to be assessed. This assessment can be applied without the need of tools, so no previous experience of particular eco-design tools is necessary.

Disadvantages:

The utilisation of this method requires some basic knowledge about which are the issues or design features that can have influence the environmental impact of LED-based lighting products. However, this basic knowledge can be substituted or complemented by eco-design guidelines, which recommend basic guidelines about eco-design. Unlike LCA-based software tools, this method requires some personal 'judgement' from the user, which will be biased by their previous knowledge about eco-design of LED-based lighting products.

Testing and analysis tools and methods:

Different types of tests and analysis (CE test, IP test, Burn-in test, Thermal test, light analysis test) have been applied in the design process. The majority of these were originally designed with the aim to increase the reliability of the lighting product and hence its lifespan, which contribute to reduce its environmental impact.

Advantages:

Tests related with reliability (CE test, IP test, Burn-in test and thermal test) are usually utilised in many traditional design processes where there is no concern to reduce the environmental impact of the lighting product, so these are not new methods and tools. High-quality lighting products are usually subject to the type of tests conducted in this case study or even to additional tests. Many of these tests (e.g. CE, IP tests) are usually outsourced, and others (e.g. burn-in and thermal tests) that do not require especial (expensive) equipment and skills (or third party authorisation) are conducted in-house by product developers.

The light analysis test, in addition to increasing the reliability of the lighting product, also provides the necessary information (luminous flux, power consumption, CCT) to conduct the environmental impact assessment with a LCA-based software tool (Simapro), and to provide parameters such as luminous efficacy (lm/W) or Light Output Ratio (LOR), which are indicators of the energy efficiency of the lighting product. The light analysis test is usually outsourced, and conducted in traditional design processes of lighting products, so no previous knowledge and skills about this test is required from product designers.

Although many of these tests contribute to improving the reliability of the lighting product, they also help to communicate to the consumer the quality of the product through the certifications (marks) provided after passing specific tests (e.g. CE, IP) successfully. Certifications such as eco-labels are one of the few ways to communicate to the environmental credentials of the lighting product the consumer so they know how it was made and its composition. This is crucial because, if the consumers cannot understand the benefits of an eco-lighting product for them, they will not demand or buy eco-lighting products, and if there is no demand; manufacturers will not produce eco-lighting products.

Disadvantages:

Although many of these tests (CE, IP, lighting tests) do not require the intervention of the product designer as they are outsourced, these are expensive and time-consuming, and many small companies cannot afford to include these in their design processes. In addition to this, these tests usually lead to further design changes (e.g. when the lighting product does not pass them), which will increase the duration of the design process. Some of these tests (thermal, burn-in tests) can usually be conducted by manufacturers in-house, but they increase the duration of the design process too. There are other quality tests-certifications (e.g. ENEC) that apply to lighting products. However, obtaining this certification does not make economic sense (Aaxsus AB), because this test is expensive, demands high-quality product standards, and there is no request from the consumer, which means that the consumer will not pay an extra price for a lighting product certified by ENEC.

Chapter 5: Method to assess and compare LED-based lighting products

This chapter describes a comprehensive and detailed method to compare and assess LED-based lighting products. The method has been applied to assess and compare the final LED-based lighting product developed in the case study with another LED-based lighting product from the same manufacturer. The method is based on the Life Cycle Assessment (LCA) methodology which is the most reliable and objective methodology available today to assess the environmental impact of products. The LCA method has been applied through a LCA-based software tool (Simapro), which allows detailed and comprehensive environmental impact assessment of lighting products. The information provided by this LCA-based method is necessary at the end of the eco-design process to inform the environmental credentials of the eco-lighting product. The chapter is divided in several sections: Chapter 5.1 (introduction), goal and scope definition (section 5.1.1), inventory analysis (section 5.1.2), life cycle impact assessment (section 5.1.3), interpretation of results (section 5.1.4), sensitivity analysis and scenarios (section 5.1.5) and Eco-design recommendations and discussion (section 5.2).

5.1 - Introduction

The LCA was carried out using Simapro software - version 7.3 (PRè Consultants, 2015b), and the following databases were used for the assessment: Ecoinvent V.2.2, ELCD and Industry data 2.0. Six scenarios were assumed in the assessment and one of them was used as the base-case scenario because it was the most probable scenario. The base-case scenario assumed that both luminaires were used, distributed and disposed in The Netherlands, with a useful life of 40,000 h. In the five additional scenarios, France was also considered as another possible location of use, distribution and disposal, and different useful lives of the luminaire were assumed.

It has to be noted that this assessment did not consider the last updated version of Simapro (Simapro V.8) and the last updated version of Ecoinvent database (Ecoinvent V.3.2) (Ecoinvent, 2015), which means that the results might differ slightly if the last updated assessment software and databases had been used.

5.1.1 - Goal and Scope definition

Goal:

The goal of this LCA was to assess and compare the new LED-based eco-lighting product developed (Figure 5.1: L2) with an existing LED-based lighting product (Figure 5.1: L1) from the company catalogue (Ona Product S.L., 2015), to know the total impact of the new developed product, to compare it with another one, and to recognise where this impact was allocated (i.e. life cycle stages, processes and components). The results of this study can be used to inform decision-making processes of product development activities such as: eco-benchmarking, eco-redesign of the LED-based lighting products assessed, and eco-design of new LED-based lighting products taking into account the findings as a reference, and Environmental Product Declarations (EPD) and eco-labels.

Scope:

The LCA was focused on two LED-based table lamps (Fig. 5.1), for indoor lighting applications, manufactured by Ona Product S.L. (Ona Product S.L., 2015). L1 was a standard lighting product that had been commercialised for several years. L2 was the eco-lighting product developed in this case study. Both lighting products could be used for decorative lighting applications.

Fig.5.1. Lighting product 1 (L1) and Lighting product 2 (L2).

L1 used one LED-lamp as a light source, while L2 used three LEDs, which each LED housed in an individual lighting module. L2 was a modular lighting product and could use up to four lighting modules, but in this LCA, the version with three modules was considered. The technical specifications of both lighting products are shown in Table 5.1, and the luminous intensity distribution curves are shown in Fig. 5.2.

	L1	L2
Weight (g)	4390.67	2133.47
Luminous flux of lighting product (lm)	102.5	948
Luminaire efficacy (lm/W)	15.29	55.11
Power consumption (W)	6.7	17.2
Light Output Ratio (LOR)	0.3	0.95
Correlated Colour Temperature (CCT) (K)	4000	5000
Colour Rendering Index (CRI)	80	65
Luminous flux of light source (lm)	340	330 (1 LED module)
Light source efficacy (lm/W)	56.66	49.25
Light source useful life	40,000 h	50,000 h
Light source	LED bulb: E-Core GLS 6W (neutral white) Toshiba	LED: CitiLED - CLL010-0305A1-50KL1A1 Citizen

Table 5.1. Technical specifications of L1 and L2.

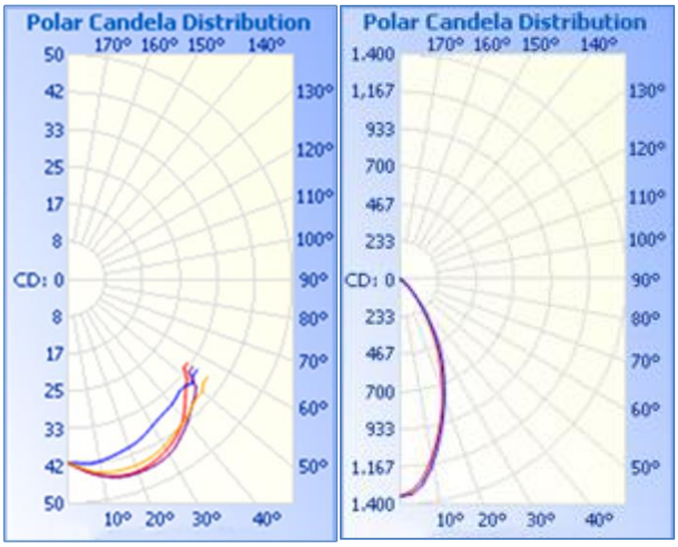


Fig.5.2. Luminous intensity distribution curves of Lighting product 1 (L1) and Lighting product 2 (L2).

<u>Functional unit:</u>

The function of a lighting product is to produce a specific quantity and quality of light for a period of time. Although both, quantity and quality, affect the electricity consumption and environmental impact of the lighting product, the quantity of light is the main contributor to the electricity consumption of the lighting product. The functional unit used in this study is the production of 948 lm, which is equivalent to the luminous flux, (i.e. the quantity of light), produced by L2 (see Table 5.1: Luminous flux of L2). In this LCA, the quality of light (i.e. Correlated Color Temperature (CCT) and Color Rendering Index (CRI)) was not taken into account in the definition of the functional unit because it is difficult to quantify the impact of differences in light quality values in a LCA. In other words, it is problematic to quantify exactly the difference in electricity consumption if the light source used in the lighting product had a CCT of 4,000 K instead of 5,000 K. This means that it is complicated to assess and compare two lighting products with different CCT values. However, in general, LEDs with 'cool' CCT (i.e. over 5,000 K) are more energy-efficient than LEDs with 'warm' CCTs (i.e. 2,700–3,000 K) (Lighting Industry Association, 2015). The difference, in terms of electricity consumption, is minimal and only represents a major difference in terms of impact when many lighting products with different CCT are compared at the same time. Since this LCA assessed and compared two LED-based lighting products with a difference in CCT of 1,000 K, the difference in terms of electricity consumption, and hence impact, was minimal.

The functional unit also has to define for how long a specific quantity and quality of light will be provided, which is determined by the useful life of the lighting product. LED-based lighting products' useful lives are usually defined using the TM-21-11 method (IES, 2011a) and is provided on LED suppliers' lifespan datasheets. However, this approach should be adopted with caution since, as discussed in several studies (US DOE, 2009a, Philips, 2014), LED lifespan datasheets cannot be used as a proxy to estimate the lifespan of a LED-based lighting product because when LEDs work as part of a lighting product in a real-world environment, their behaviour may be different to the same LEDs tested outside lighting products in controlled-lab environments. This has been confirmed in several studies, which show that LED-based lighting products can fail before their expected useful life (US DOE 2009b, Casamayor et al. 2015). This suggests the need to consider several possible useful lives 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 (ideal) failure due to natural wear out of components.

One of the problems when conducting LCA of LED-based lighting products is that it is difficult to estimate realistically how long the lighting product will last (useful life) unless the lighting product manufacturers provide information about the useful life of the lighting products to be compared. When different useful lives are assumed for each lighting product, the environmental impact results for each lighting product will change drastically, since the use stage is the highest contributor in terms of impact. If useful life assumptions are considered equally in both lighting products, as it has been carried out in this LCA, the results will be objective and valid, but assuming that one luminaire will last more than the other in a comparative LCA based on personal subjective judgement (not based on factual data) will affect the validity of the results. Although the new lighting product developed might have a longer useful lifespan as a result of better design and construction, the useful lifespan considered in all the scenarios of this LCA is the same, since there was not available factual data from the manufacturer about the useful life of both lighting products.

<u>System boundaries:</u>

The boundaries of this LCA comprise cradle to grave life cycle processes. The product life cycle stages included in this assessment are: Extraction and production of materials, manufacturing, distribution, use and end of life of the lighting products. The manufacturing of the packaging has not been considered in the assessment (Fig. 5.3).

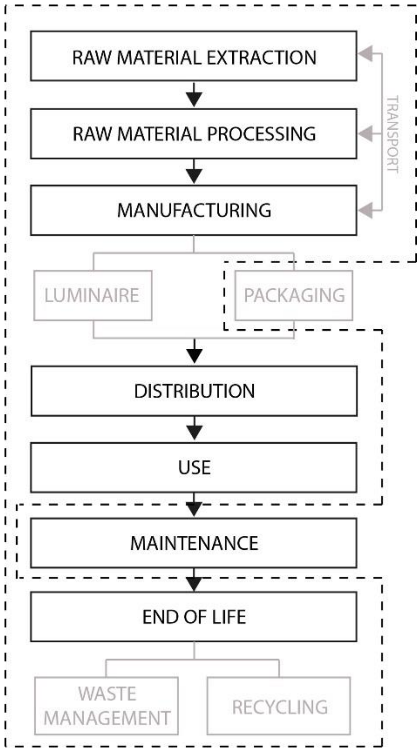


Fig.5.3. Product System boundaries.

Specific data has been omitted, and certain assumptions have been considered during the definition of the system boundaries of the lighting products' life cycle, including the following:

Materials extraction/production and manufacturing:

The transport from the materials extraction site to the materials production factory, and from the materials production factory to the final product assembly factory has not been taken into consideration in the assessment as an additional process. However, the transport from the materials extraction site to the materials production factory is already accounted for in some manufacturing processes databases, although not in all of them.

The material used for the casings (100% recycled PET) was accounted in the assessment as no material used since it is 100% used from recycled post-consumer sources.

Use:

The maintenance of the lighting product during use was not considered in the assessment. Maintenance may cause extra impact during the 'use' stage, but it can also extend the useful life of the lighting product by improving its efficacy (i.e. clean optical elements produce more light output).

Distribution:

This stage only considered the distribution of the lighting product from the factory based in Spain to the final consumer in Netherlands and France. It did not include the transport of the raw materials to the materials production factory, the transport of the materials and components to the factories that produced the semi-finished assemblies or components, the distribution of the lighting product from the retailer to the final consumer's house, and the transport from the disposal point to the waste or recycling management factory.

For the distribution of the lighting product from the factory in Spain to the retailer in the Netherlands, it was assumed a total distance of 2,063 km. This distance comprised two sub-distances: the distribution from ONA factory to the Netherlands national point of the logistic company (1874 km), using 40-Tonnes lorries, and the distribution from the Netherlands national point of the logistic company to the retailers (189 km), using 3.5-7.5 Tonnes lorries.

For the distribution of the lighting product from the factory in Spain to the retailer in France, it was assumed a total distance of 1,566 km. This distance comprised the distribution from ONA factory to France national point of the logistic company (1,377 km.)

using 40-Tonnes lorries, and the distribution from the France national point of the logistic company to the retailers (189 km.) using 3.5-7.5 Tonnes lorries.

End of Life:

The disposal of the lighting products depends on consumers' personal decisions, so it was difficult to predict exactly how each lighting product used was going to be disposed (i.e. in the domestic bin, recycling centre).

Understanding these uncertainties, it was assumed that both lighting products were disposed in the domestic bin, and followed the usual path of household municipal waste in two countries (Netherlands and France), and existing scenarios for treatment of municipal waste in both countries were used in the assessment.

5.1.2 - Inventory analysis

The Bill of Materials (BoM) of both lighting products is shown in appendixes 5.1 and 5.2. The list of manufacturing processes used to produce and shape the materials used to make each lighting product are shown in appendixes 5.3 and 5.4, and the list of distribution, electricity production and End of Life (EoL) treatment processes are shown in appendix 5.5. The materials and processes data were selected from the following databases: Ecoinvent, European reference Life Cycle Database (ELCD), and Industry data 2.0.

5.1.3 - Life Cycle Impact assessment

Eco-indicator 99 LCIA method (Goedkoop and Spriensma, 2001), the hierarchist perspective, was selected for the assessment. This method was selected because it provides single score results which allows easier comparison between products. A hierarchist perspective was selected because it is the 'by default' option of this method as it presents an 'intermediate' middle term approach to value choices and damages based on average weighting, which satisfies different groups. Using an end point method also facilitates decision making, since it is easier to see which product, process or component has higher impact. It also facilitates the communication of environmental impact results to stakeholders who are not familiar with impact categories such as product developers and management, because it communicates the results using a single score. Since the aim of the assessment was to inform decision-making processes of the product development staff and management from a company, it was considered that this method was suitable in this case.

In the Eco-indicator 99 method, normalisation and weighting are performed at damage category level. There are three damage categories: Human Health (HH), Ecosystem Quality (EQ) and Resources (R), and eleven impact categories: Fossil Fuels, Minerals, Land Use, Acidification/Eutrophication, Ecotoxicity, Ozone Layer, Radiation, Climate Change, Respiratory Inorganics, Respiratory Organics and Carcinogens.

5.1.4 - Interpretation of results

This section shows the results based on the base-case scenario only, where it was assumed that L1 and L2 were distributed, used (useful life: 40,000 h), and disposed in The Netherlands. The results of the two lighting products were presented in damage categories (Table 5.7), impact categories (Table 5.8), life cycle stages (Table 5.9) and processes (Tables 5.10 and 5.11).

<u>Results - damage and impact categories</u>

As shown in tables 5.7 and 5.8, L1 had 3.2 times higher total environmental impact (L1, 154 Pt; L2, 36.6 Pt) than L2, in both damage and impact categories.

Damage category	Unit	L1	Impact % (L1)	L2	Impact % (L2)
Total	Pt.	*154*	*100%*	*36.6*	*100%*
Human health	Pt.	53.6	35%	12.8	35%
Ecosystem quality	Pt.	16.4	11%	2.43	7%
Resources	Pt.	83.5	54%	21.3	58%

Table 5.7. Total and per damage category environmental impact of L1 and L2 in the base-case scenario.

Impact category	Unit	L1	Impact % (L1)	L2	Impact % (L2)
Total	Pt.	*154*	*100%*	*36.6*	*100%*
Carcinogens	Pt.	15.6	10%	4.44	12%
Respiratory organics	Pt.	0.0163	0%	0.0031	0%
Respiratory inorganics	Pt.	23	15%	4.56	12%
Climate change	Pt.	14.8	10%	3.78	10%
Radiation	Pt.	0.124	0%	0.0322	0%
Ozone layer	Pt.	0.00307	0%	0.0007	0%
Ecotoxicity	Pt.	13.2	9%	1.73	5%
Acidification/ Eutrophication	Pt.	1.79	1%	0.418	1%
Land use	Pt.	1.41	1%	0.281	1%
Minerals	Pt.	3.21	2%	0.618	2%
Fossil fuels	Pt.	80.3	52%	20.7	57%

Table 5.8. Total and per impact category environmental impact of L1 and L2 in the base-case scenario.

Results - life cycle stages and processes

Table 5.9 shows the absolute (in Pt.) and relative (%) impact of each life cycle stage and the total environmental impact of each lighting product. The life cycle stage with the highest impact in the base-case scenario in both lighting products is the 'use' stage, where L1 had an impact of 122 Pt. and L2 had an impact of 33.8 Pt., followed by the 'manufacturing', 'end of life', and 'distribution' stages. The 'use' stage accounted for 92% of the total impact of L2 and 79% in L1. This is due to the higher environmental impact of the 'manufacturing' stage of L1 in comparison with L2.

Life cycle stage	Unit	L1	Impact % (L1)	L2	Impact % (L2)
Total	Pt	*154*	*100%*	*36.6*	*100%*
Manufacturing	Pt	24.1	16%	2.05	6%
Distribution	Pt	1.609	1%	0.0845	0%
Use	Pt	122	79%	33.8	92%
End of Life	Pt	6.06	4%	0.622	2%

Table 5.9. Environmental impact per life cycle stage of L1 and L2 in the base-case scenario.

Process	Database	Unit	Impact	Impact %
Electricity, low voltage, production NL, at grid/NL S	Ecoinvent	Pt	122	79%
Drilling, conventional steel/RER S	Ecoinvent	Pt	10.3	7%
Stainless steel hot rolled coil, annealed & pickled, elec.arc furnace route, prod. Mix, grade 304 RER S	ELCD	Pt	6.97	5%
Disposal, copper,0% water, to municipal incineration/CH S	Ecoinvent	Pt	4.88	3%
Pig iron, at plant/GLO S	Ecoinvent	Pt	1.38	1%
Truck 40t	LCA Food DK	Pt	1.26	1%
Disposal, steel, 0% water, to municipal incineration/CH S	Ecoinvent	Pt	1.06	1%
Laser machining, metal, with CO2-laser, 2000W power/RER S	Ecoinvent	Pt	1.02	1%
Printed wiring board, surface mount, lead-free surface, at plant/GLO S	Ecoinvent	Pt	0.729	0%
Welding, arc, steel/RER S	Ecoinvent	Pt	0.508	0%
Copper, primary, at refinery/GLO S	Ecoinvent	Pt	0.498	0%
PVC injection moulding E	Industry data 2.0	Pt	0.366	0%
Light Emitting Diode, LED, at plant/GLO S	Ecoinvent	Pt	0.277	0%
Disposal, sulfidic tailings, off-site/GLO S	Ecoinvent	Pt	0.203	0%
Capacitor, Tantalum-, through-hole mounting, at plant/GLO S	Ecoinvent	Pt	0.192	0%
Iron ore, 46% Fe, at mine/GLO U	Ecoinvent	Pt	0.19	0%
Paper, wood-containing, LWC, at regional storage/RER S	Ecoinvent	Pt	0.176	0%

Table 5.10. Environmental impact (shown in single score) per process of L1 in the base-case scenario.

Table 5.10 shows the absolute impact (in Pt.), and the relative impact (%) of each process included in the total environmental impact of L1. Table 5.11 shows the absolute impact (in Pt.), and the relative impact (%) of each process included in the total environmental impact of L2. It has to be noted that the results shown in tables 5.10 and 5.11, consider a 0.1% cut-off to avoid including processes with a minor impact in the tables.

Process	Database	Unit	Impact	Impact %
Electricity, low voltage, production NL, at grid/NL S	Ecoinvent	Pt	33.8	93%
Aluminium alloy, AlMg3, at plant/RER S	Ecoinvent	Pt	0.598	2%
Disposal, copper, 0% water, to municipal incineration/CH S	Ecoinvent	Pt	0.531	2%
Milling, aluminium, small parts/RER S	Ecoinvent	Pt	0.377	1%
Integrated circuit, IC, logic type, at plant/GLO S	Ecoinvent	Pt	0.212	1%
Inductor, unspecified, at plant/GLO S	Ecoinvent	Pt	0.198	1%
Printed wiring board, through-hole mounted, unspec. Pb-free, at plant/GLO S	Ecoinvent	Pt	0.145	0%
Transformer, low voltage use, at plant/GLO S	Ecoinvent	Pt	0.093	0%
Polymethyl methacrylate (PMMA) beads, production mix, at plant RER	ELCD	Pt	0.0862	0%
Light Emitting Diode, LED, at plant/GLO S	Ecoinvent	Pt	0.0847	0%
Capacitor, electrolyte type, < 2cm height, at plant/GLO S	Ecoinvent	Pt	0.0767	0%
Resistor, SMD type, surface mounting, at plant/GLO S	Ecoinvent	Pt	0.0687	0%
Disposal, municipal solid waste, 22.9% water, to municipal incineration/CH S	Ecoinvent	Pt	0.0667	0%
Truck 40t	LCA food DK	Pt	0.0663	0%
Copper, primary, at refinery/GLO S	Ecoinvent	Pt	0.0539	0%
Capacitor, unspecified, at plant/GLO S	Ecoinvent	Pt	0.0433	0%
PVC injection moulding E	Industry data 2.0	Pt	0.0399	0%
Printed wiring board. Through-hole, lead-free surface, at plant/GLO S	Ecoinvent	Pt	0.0389	0%
PET (bottle grade) E	Industry data 2.0	Pt	-0.441	0%

Table 5.11. Environmental impact (shown in single score) per process of L2 in the base-case scenario.

The total environmental impact of L1 was much higher than L2 (154 vs. 36.6). In both lighting products, the life cycle stage with the highest impact was the ‘use’ stage, followed by the ‘manufacturing’, ‘end of life’, and ‘distribution’ stages.

The ‘damage’ and ‘impact’ categories with the highest impact were the ones related with the production of electricity, which is related with the ‘use’ stage. The ‘impact’ categories with the highest impact were: Fossil fuels (80.3 pt.) in L1 and Fossil fuels (20.7 Pt.) in L2.

In L2, the ‘use’ stage had a higher relative impact (92 % vs. 79%) out of the total impact in comparison with L1. This is because the ‘manufacturing’ stage in L1 had higher relative impact out of the total impact in comparison with L2 (16 % vs. 6%), and because L1 had less luminous efficacy than L2 (L1: 15.29 lm/W vs. L2: 55.11 lm/W). The ‘distribution’ and ‘end of life' stages had a minor relative impact in both luminaires (L1: distribution: 1% and EoL: 4%; L2: distribution: 0% and EoL: 2%).

The process with the highest impact in both lighting products was 'electricity production', which accounts for the process used to produce electricity consumed by the lighting products in the 'use' stage. The 'manufacturing' stage was the second highest impact life cycle stage in both lighting products. The manufacturing processes with the highest impact in L1 were: Drilling of the stainless steel main structure frame (10.3 Pt.), stainless steel production that was used in the main structure frame (6.97 Pt.) and production of iron used in the base (1.38 Pt.). The manufacturing processes with the highest impact in L2 were: Aluminium alloy production used in the base, pole and heat sinks (33.8 Pt.), aluminium milling to make the heat sinks (0.377 Pt.) and the production of the integrated circuit component used in the circuit system (0.212 Pt.), which was made of several components. In the 'use' stage, which is the stage with the highest impact, L1 had higher impact than L2 because the efficacy (light produced/consumption of energy) of L1 was much lower than L2. In the 'manufacturing' stage L1 had higher impact because it used more material (higher total material weight) and also because the production of the type of material used (Stainless steel and iron) had higher impact than the production of the main material (recycled PET) used in L2. In addition, since more material was used in L1 more material had to be processed, which meant higher impact in manufacturing-shaping processes in comparison with L2. The type of manufacturing processes used to shape the material used to make the housing in L2 (e.g. injection moulding) had lower impact (presumably because it is more efficient: less energy consumed and less waste produced) than the manufacturing processes used in L1 (e.g. machining processes such as drilling, cutting). Although in L2 the machining processes were also used to shape the aluminium heat sinks, the amount (weight) of material to be processed was minor, because the main material used in the housing of L2 was recycled PET. Additionally, the parts used in L1 were coated whilst the parts in L2 were not, which further increased the difference in impact in the 'manufacturing' stage. In the 'end of life' stage L1 has also higher impact than L2 because, more material (weight) had to be processed, but the impact of this stage is marginal, and hence it does not contribute to major difference between the total impact of L1 and L2.

5.1.5 - Sensitivity analysis and scenarios

In order to check the sensitivity of the results and to find out what would be the impact of the lighting products when these have different useful lives, and are used, distributed, and disposed in different countries (Netherlands and France), six scenarios were assumed (Table 5.12). One of these scenarios (base-case scenario) was considered the base-case scenario because it was the most probable:

Scenarios	Country where is Manufactured	Country where is used	Useful life	Country where is distributed	Country where is disposed
Base-case	Spain	The Netherlands	40,000 h	The Netherlands	The Netherlands
Scenario 1	Spain	The Netherlands	15,000 h	The Netherlands	The Netherlands
Scenario 2	Spain	The Netherlands	1,000 h	The Netherlands	The Netherlands
Scenario 3	Spain	France	40,000 h	France	France
Scenario 4	Spain	France	15,000 h	France	France
Scenario 5	Spain	France	1,000 h	France	France

Table 5.12. Scenarios description.

The sensitivity analysis and scenarios were focused on the ‘use’ stage because it was the stage with the highest impact. Two of the parameters that can affect the environmental impact of the ‘use’ stage are: 1) The energy mixes used to power the lighting product during the ‘use’ stage, and 2) The useful life of the lighting product. The useful life will differ depending on manufacturing faults, operating conditions, and lighting product design (US DOE, 2009a). A ‘lumen depreciation long-term performance study’ carried out by US DOE (2009b) showed that 5 out of 26 LED-based lighting products failed to produce their intended light output (below 70% of its light output: also called L70) within the first 1,000 h, which shows that LED-based lighting products do not always have the useful life provided by the LED suppliers, but rather follow the typical ‘bathtub’ curve of electronic products, which shows three key periods of possible failure: ‘Early failure period’, ‘spontaneous failure period’ and ‘wear out period’ (Osram, 2008).

In order to account for these possible useful life scenarios, three scenarios were assumed: 1,000 h (early failure period), 15,000 h (spontaneous failure period) and 40,000 (wear out period). The scenario of 15,000 h was created to account for a random failure, or when the lighting product is substituted due to technology or aesthetics upgrade. The scenario of 40,000 h corresponded to the useful life provided by the LED supplier, which is usually determined by natural wear and tear and degradation of materials and components in normal (as suggested by the manufacturer) operating conditions.

The scenarios also assumed the possibility that the lighting products could be purchased and used in different countries (The Netherlands and France), where different energy mixes and disposal and waste systems might apply.

Tables 5.13 and 5.14 show the total environmental impact and the environmental impact per life cycle stage of both luminaires (L1 and L2) assuming six scenarios (the base-case scenario and five additional scenarios). The results are shown in absolute impact (Pt.) and relative impact (%).

Scenarios	Unit	L1				
		Life cycle stage				
		Manufacturing	Distribution	Use	End of Life	Total
Base-case scenario	Pt	24.1 (16%)	1.609 (1%)	122 (79%)	6.06 (4%)	*154 (100%)*
Scenario 1	Pt	24.1 (31%)	1.609 (2%)	45.6 (59%)	6.06 (8%)	*77.4 (100%)*
Scenario 2	Pt	24.1 (69%)	1.609 (5%)	3.04 (9%)	6.06 (17%)	*34.8 (100%)*
Scenario 3	Pt	24.1 (34%)	1.27 (2%)	40.5 (57%)	4.67 (7%)	*70.6 (100%)*
Scenario 4	Pt	24.1 (53%)	1.27 (3%)	15.2 (34%)	4.67 (10%)	*45.3 (100%)*
Scenario 5	Pt	24.1 (78%)	1.27 (4%)	1.01 (3%)	4.67 (15%)	*31.1 (100%)*

Table 5.13. Total environmental impact per life cycle stage of L1 in all scenarios

Scenarios	Unit	L2				
		Life cycle stage				
		Manufacturing	Distribution	Use	End of Life	Total
Base-case scenario	Pt	2.05 (6%)	0.084 (0%)	33.8 (92%)	0.622 (2%)	*36.6 (100%)*
Scenario 1	Pt	2.05 (13%)	0.084 (1%)	12.7 (82%)	0.622 (4%)	*15.4 (100%)*
Scenario 2	Pt	2.05 (57%)	0.084 (2%)	0.846 (24%)	0.622 (17%)	*3.6 (100%)*
Scenario 3	Pt	2.05 (15%)	0.066 (1%)	11.2 (81%)	0.44 (3%)	*13.8 (100%)*
Scenario 4	Pt	2.05 (30%)	0.066 (1%)	4.22 (62%)	0.44 (7%)	*6.77 (100%)*
Scenario 5	Pt	2.05 (72%)	0.066 (2%)	0.281 (10%)	0.44 (16%)	*2.84 (100%)*

Table 5.14. Total environmental impact per life cycle stage of L2 in all scenarios.

Although L2 had lower environmental impact than L1, both lighting products had the highest total environmental impact in the base-case scenario (Netherlands – 40,000 h), and the lowest environmental impact in scenario 5 (France – 1,000 h). The 'use' stage was the life cycle stage with the highest impact except in scenarios 2, 4 and 5 in L1 and Scenarios 2 and 5 in L2. In scenarios 2, 4 and 5 for L1, and scenarios 2 and 5 for L2, the highest impact was in the ‘manufacturing’ stage due to the shorter useful life assumed in scenarios 2, 4 and 5 which reduced the relative impact of the ‘use’ stage. Since L1 had a higher absolute impact in the ‘manufacturing’ stage than L2 (24.1 vs. 2.05), in L1 the ‘manufacturing stage’ had higher impact than other life cycle stages in more scenarios than L2. The ‘end of life’ and ‘distribution’ stages had a minor impact in all scenarios (i.e. L1: Base case, Scenario 1 and Scenario 2: 6.06; Scenario 3, Scenario 4 and Scenario 5: 4.67. and for L2: Base case, Scenario 1 and Scenario 2: 0.622; Scenario 3, Scenario 4 and Scenario 5: 0.44).

When it was assumed scenarios where the lighting products were used in other countries (i.e. France), rather than the country of the base-case scenario, with other useful lives scenarios (1,000 h and 15,000 h), L1 still had higher total impact than L2. However, the absolute and relative impacts of both luminaires in each life cycle stage differed in each scenario as it is shown in Tables 5.13 and 5.14.

In general, when the lighting product was assumed to function for a longer period of time (longer useful life), the environmental impact was higher. However, when both luminaires were assumed to function for the same period of time in different countries the impact differed. The use of Dutch energy mix to power the luminaire had higher impact than the use of French energy mix (L1-Base-case scenario; French energy mix: 40.5 pt. and Dutch Energy mix: 122 pt.) because the French energy mix was supplied from different sources that had less impact. Table 5.15 shows how the French energy mix produces a higher amount of electricity from renewables (i.e. wind, tide, solar, hydro) than the Dutch energy mix. It also has a much higher supply from nuclear, and rely less on energy supplied from burning fossil fuels (coal, oil, and gas). This may explain the higher impact of using the Dutch energy mix in comparison with the French energy mix.

Source of supply	The Netherlands	France
Coal	27539	24811
Oil	1248	2485
Gas	55164	17174
biofuels	3879	3104
Waste	3774	3814
Nuclear	2891	423685
Hydro	114	75640
Solar PV	516	4661
Wind	5627	16033
Tide		414
Other sources	127	696

Table 5.15. Energy mixes composition from France and The Netherlands.

In all the scenarios, the ‘distribution’ and ‘end of life’ stages had a minor impact. The reduced distribution distance in the scenarios where the lighting products were distributed to France instead of Netherlands, meant less distribution impact, in particular for the lighter lighting product L2.

It is interesting to see how short useful lives shifts the life cycle stage with the highest impact from the ‘use’ stage to the ‘manufacturing’ stage. For instance, if a scenario where the LED-based lighting product fail prematurely is assumed (i.e. within the first 1,000 h of useful life), the ‘use’ stage will not be the life cycle stage with the highest impact. In this case, the ‘manufacturing stage’ will have the highest impact, which means that the eco-design efforts to reduce the impact of the lighting product will have to be focused on the ‘manufacturing stage’. However, if a long useful life is considered (i.e. 40,000 h) where the LED-based lighting product is used in ‘ideal’ (following the manufacturer recommendations) operating conditions, then the ‘use stage’ will have the highest environmental impact, and hence the eco-design efforts should be focused on this stage. It would be interesting to compare these lighting products with different useful lives (additional scenarios), in order to find out and compare the environmental impact of durable well-made lighting products vs. lighting products with short useful lives.

5.2 - Eco-design recommendations and discussion

The results of this LCA-based assessment can be used for several purposes: 1) To know the total (and per category) impact of the LED-based lighting product developed, 2) To eco-benchmark other LED-based lighting products manufactured by the same, or other, companies, 3) To eco-redesign the LED-based lighting products assessed, 4) To have a general reference about typical life cycle stages and components with higher impact in LED-based luminaires, and 5) To understand how different possible scenarios could affect the total impact, and the impact of each life cycle stage. This LCA showed that L2 had lower environmental impact than L1, and also revealed the life cycle stages and materials-components-processes (within the manufacturing stage) with the highest impact, where eco-design strategies could be implemented to reduce the environmental impact of both lighting products.

The life cycle stages with the highest impact in both lighting products were: the 'use' and 'manufacturing' stages. The main eco-design strategies identified to reduce the impact of both lighting products in these life cycle stages were: In the 'Use' stage: a) Increase the luminous efficacy of the lighting product, and b) integrate smart controls (i.e. occupancy sensors) to reduce the energy used during the 'use' stage.
In the 'Manufacturing' stage: In L2: 1) Use of 100% recycled aluminium to manufacture the heat sinks, pole and base, in order to reduce the impact of sourcing aluminium virgin material, 2) Avoid machining processes (i.e. milling) to manufacture some components (i.e. heat sinks) because these manufacturing processes are less efficient in terms of energy consumption, material use and production of waste. Aluminium could also be substituted by recycled PET in order to use the same recycled materials as it is used in the lighting modules.
In L1: 1) Use of 100% recycled steel to manufacture the main frame, in order to reduce the impact of sourcing virgin steel material, 2) Use of 100% recycled iron to manufacture the base, in order to reduce the impact of sourcing virgin iron material. Steel and iron materials could also be substituted by another recycled low-impact material.

For a short useful life (i.e. 1,000 h.), the 'manufacturing' stage was the life cycle stage with the highest impact, instead of the 'use' stage. This scenario may happen in LED-based lighting products with production faults or used in extreme operating conditions. In this case, eco-design strategies have to be focused on the 'manufacturing' stage first, followed by the 'use' stage.

In order to provide valid and realistic LCA comparative results between LED-based lighting products, it is necessary to have access to factual data about: useful life of each lighting product, the reduction-percentage (factor) to be applied to the useful life of each lighting product to account for their performance related with light control (i.e. dimming); the reduction-percentage (factor) to be applied in the useful life of both lighting products to account for easy disassembly for repair/maintenance; and the recycling-percentage (factor) of each LED-based lighting product based on its architecture and composition. All these features significantly affect the useful life, which is directly related with the ‘use’ stage, the life cycle stage with the highest impact by far, so the study of how these features may affect the LCA is important for comparative LCA of LED-based lighting products. Some of these features also affect the ‘end of life’ stage, since lighting products 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-based lighting products.

Chapter 6: Lifespan of LED-based lighting products

During the description and examination of the case study (Chapter 4) the key product-related issues that influence the environmental impact of LED-based lighting products were identified. One of the identified issues was the lifespan of the lighting product. Lighting products that last longer produce less environmental impact, so it was necessary to study how we can design LED-based lighting products to last longer. In order to extend the lifespan of the LED-based lighting product it is necessary to understand why LED-based lighting products end their useful lives and when, to inform the creation of eco-design strategies that can be implemented during the design process to extend their lifespan. The understanding of the real lifespan (based on field real world data) can also inform LCA, since the estimated lifespan considered in LCA of LED-based lighting products, is usually based on the lifespan of the light source (LED) used in the lighting product, and this does not reflect the actual real lifespan. This chapter presents a study about the lifespan of LED-based lighting products in order to understand why they fail and when, in order to inform the creation of eco-design guidelines that can be used in eco-design processes to contribute in extending the lifespan of LED-based lighting products.

6.1 - Introduction

The technical lifespan of LED-based lighting products depends on the reliability of the components and materials (electronics, housing, wiring, connectors, seals) that makes the lighting product (US DOE, 2009b). The lighting product will not stop functioning until one of the components fails. LEDs are only one of the components that may fail among many others. LED-based lighting products lives may end because of functional failure of any of their components, or because the light output produced is below a minimum threshold, due to degradation (wear-out) of their components over time. In this study, the term 'lifespan' refers to the lifespan of the lighting product from the beginning of its functioning life until the End of life (EoL) with the first owner (Murakami, Oguchi, Tasaki, Daigo, & Hashimoto, 2010).

LEDs, unlike other types of light sources, do not usually fail abruptly, instead, their light output slowly diminishes over time (US DOE, 2009b). This means that LEDs can still work after long periods of time (50.000+ h.), but their light output may decrease so much over time that they may fail to maintain the initial lighting quantity and quality required, and therefore their 'useful life' will be considered finished, although they can still function.

For example, in a lighting product used in buildings, the 'useful life' of the LED will end when the LED reaches 70% of its initial light output. A typical LED lifespan, like any other electrical-electronic component, can be described by three clear stages: (1) early failures, (2) spontaneous failures, and (3) wear out period (Fig. 6.1).

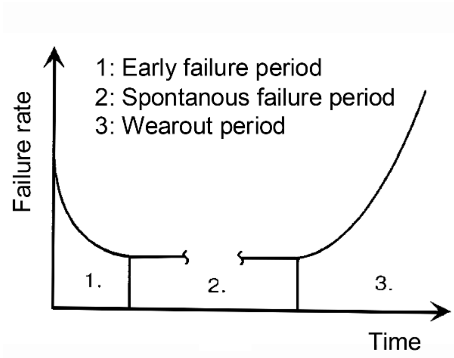


Figure 6.1. Bathtub curve.

The first period (early failure period) is usually caused by defective materials, deviations in the manufacturing process or by incorrect handling and operation by the distributor and/or the customer. The second period (spontaneous failure period) is usually caused by spontaneous and random failures, and the last period (wear out period) is usually generated by natural degradation of materials and components over time, which leads to the reduction of light output and/or failure (Osram, 2008). As shown in Fig. 6.1, in the 'spontaneous failure' period the failure rate is low.

Although the LED component is sometimes the cause of the end of life of the LED-based lighting product, there are other causes such as: driver failure, cooling system failure, dimmer failure, control unit failure, inadequate light output quality (colour render index: CRI, colour correlated temperature: CCT), and need for new aesthetic/functionality. Fig. 6.2 shows the various causes that can cause the end of life and replacement of LED-based lighting products.

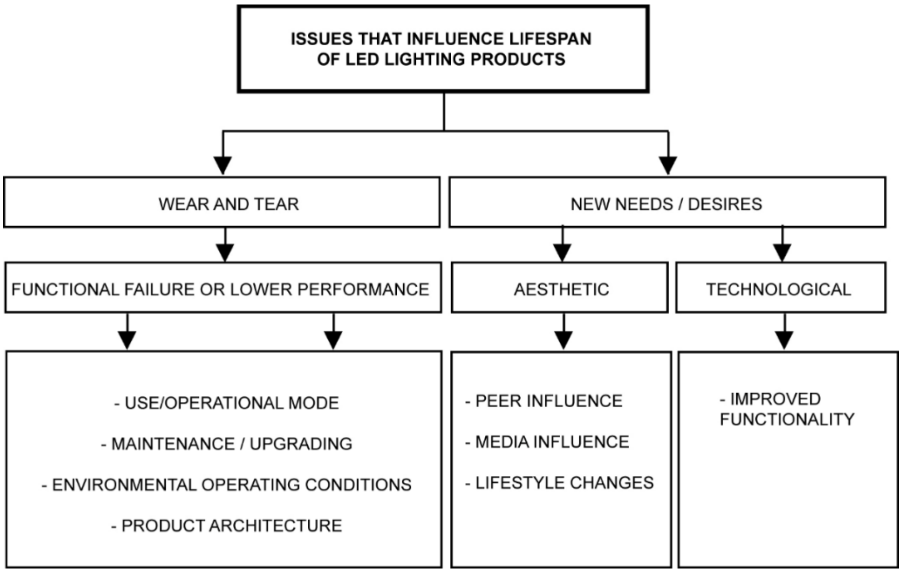


Figure 6.2. Causes of the end of life of LED-based lighting products.

6.2 - Methodology

The methodology used in this study consisted of the distribution of two types of close-ended questionnaires. One for LED-based lighting product manufacturers and another for LED-based lighting product users/consumers (individual consumers, facilities management, companies and retailers). The questionnaire designed for manufacturers consisted of 15 questions, and the questionnaire for consumers contained 17 questions.

The questionnaires were designed and piloted with input from LED-based lighting product manufacturers who participated in this study, including Braun Lighting Solutions E.K. (Braun, 2015) in Germany, Etap N.V. (Etap, 2015) in Belgium, LED in Light Ltd. in UK, and Ona Product S.L. (Ona, 2015) in Spain. In addition to this, several research centres (Fraunhofer IZM E.V., ELPRO GmbH., Eco-design Centre Wales, Sirris V.Z.W, and Optotransmitter Umweltschutz Technologie E.V.) provided feedback about the design of the questionnaire carried out by the author:

The questionnaire design included questions about the following issues:

1. When did the lighting products fail or when were replaced?
2. What were the causes of these failures?
3. What were the environmental and operational conditions leading to failures?
4. What happened (i.e. they were repaired, disposed) after the lighting products failed?

Both, the manufacturer and consumer, questionnaires were translated into three languages (English, German and Spanish) for the sample of the participants located in four countries (Belgium, Germany, Spain, UK), and were distributed and sponsored by each company in each country. The self-completion questionnaires were distributed on-line, to a sample of 1,691 participants: 396 LED-based lighting product manufacturers and 1,295 LED-based lighting product consumers. Out of the 1,691 questionnaires distributed, 140 were completed, of which 83 were from consumers and 57 from manufacturers.

The survey cover letter (appendix 6.1) and the questionnaires for the manufacturers (appendix 6.2) and consumers (appendix 6.3) have been attached in the appendix.

6.3 - Questionnaire results

The results are divided in two sections: Actual lifespan of LED-based lighting products and LED-based lighting product lifespan in worst and best case scenarios.

<u>Actual lifespan of LED-based lighting products:</u>

This section explains the results related to the actual lifespan of LED-based lighting products used in real world operating conditions. The lifespan of LED-based lighting products was derived from these parameters:

1. Service years: Represent how many years the LED-based lighting product was used before it reached the end of life.

2. Daily use hours: Represent how many hours per day the LED-based Lighting product was used within its service years.

Fig. 6.3 and 6.5 are related to the service years, while Fig. 6.4 and 6.6 are related to the daily use hours. As it is shown in Fig. 6.3, respondents of consumers' questionnaires revealed that out of 31.71% of LED-based lighting products that failed (Fig. 6.7), 79.31% failed in the first year, 17.24% in the second year, and 3.45% in the third year, no failure was reported after the third year.

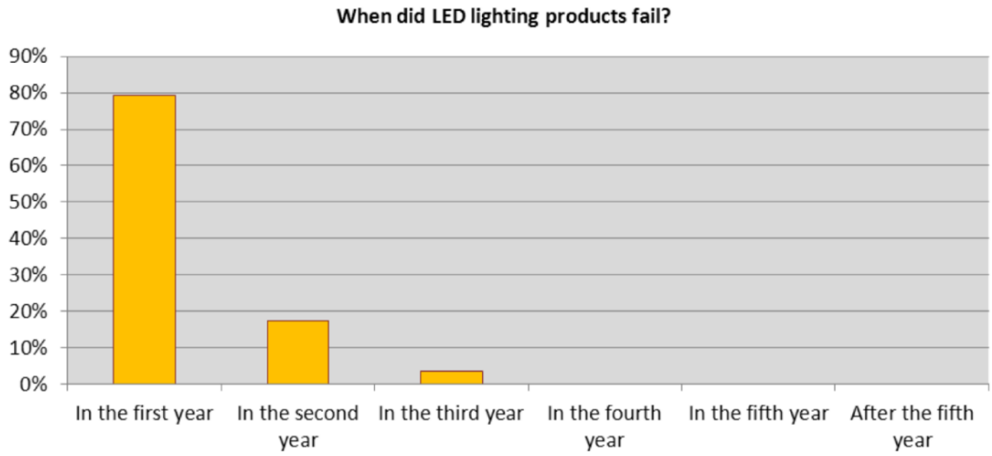


Figure 6.3. LED-based lighting products' failure percentage vs. years of use – consumers' questionnaire results.

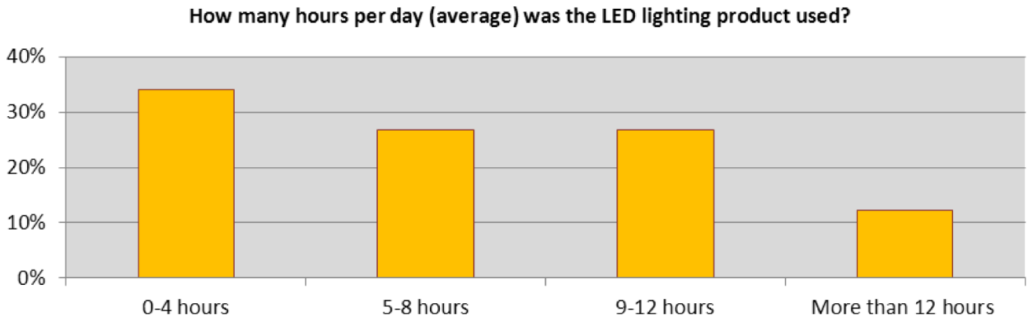


Figure 6.4. LED-based lighting products hours of use per day – consumers' questionnaire results.

Amongst the LED-based lighting products (reported by consumers-users) that failed during the first, second and third year (Fig. 6.3), 34.15% of them were used 0–4 h. per day, 26.83% of them were used 5–8 h. per day, and 12.20% were used 12 h. per day (Fig. 6.4).

Results of manufacturers' questionnaires showed that out of 31.71% of LED-based lighting products that failed (Fig. 6.7), 59% failed in the first year, 22% in the second year, 10% in the third year, 4% in the fourth year, 2% in the fifth year, and 4% after the fifth year, as it is shown in Fig. 6.5.

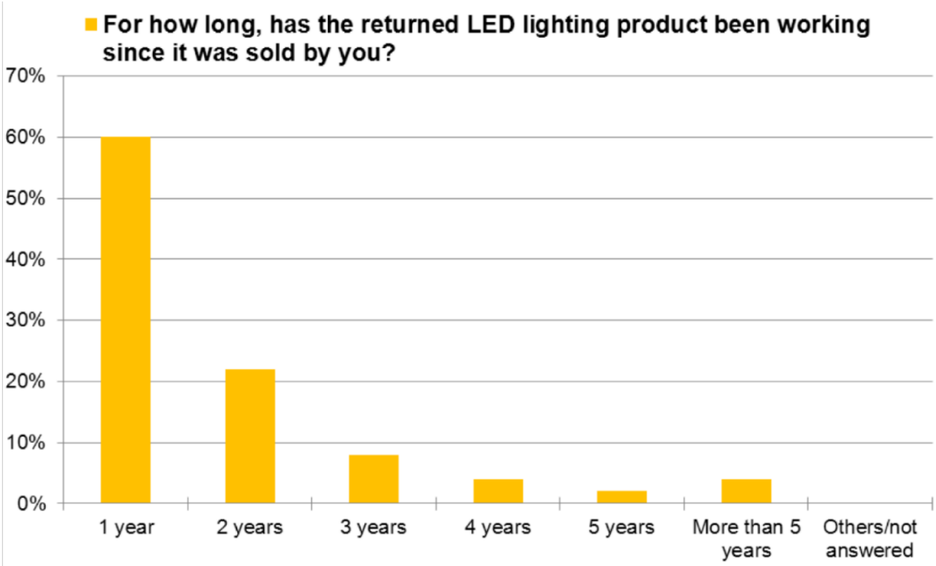


Figure 6.5. LED-based lighting products actual lifespan – manufacturers' questionnaire results.

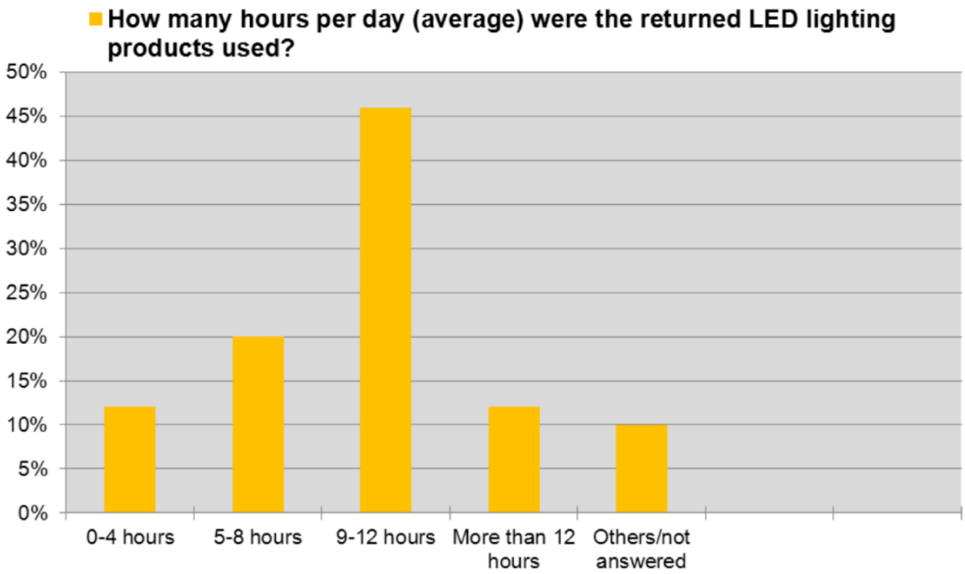


Figure 6.6. LED lighting products – hours of daily use per day – manufacturers' questionnaire results.

Amongst the LED-based lighting products (reported by manufacturers) that failed during the first, second, third, fourth and fifth year (Fig. 6.5), 46% of them were used for 9-12 h., 20% of them were used for 5–8 h., and 12%. were used for 0–4 h. and 12 h. (Fig. 6.6)

<u>LED-based lighting product lifespan in worst and best case scenarios:</u>

The lifespan of a LED-based lighting product is measured by its use (in h.) before it reaches its EoL. It can be calculated by: L = h∗(Y∗365), where L is the lifespan of the product, measured in h., h is the daily use (in h.) and Y is the service years.

According to the data provided by the questionnaires, it was impossible to find the exact daily use hours (i.e. the number of hours a lighting product had been used per day) within each service year (Y), and, hence, it was not possible to derive a single number to represent the LED-based lighting product lifespan. As a solution, this research used two scenarios, the 'worst case scenario' and the 'best case scenario'. In the worst case scenario, the service years with the highest failure percentage (Yw) and the daily use hours with the lowest number of daily service hours (hw) were used to calculate the worst scenario lifespan (Lw). In the best case scenario, the service years with the least failure percentage (Yb) and the highest number of daily service hours (hb) were used to calculate the best case scenario lifespan (Lb).

In the best case scenario, LED-based lighting products had almost no failure after 3 years of use (Fig. 6.3), in this case, 5 years was considered as the best case scenario-service years (Yb = 5), when lighting products were used more than 12 h per day (Fig. 6.4), in this case it was considered 15 h. Therefore, in the best case scenario, the product failed after 3 years of use (in this case 5 years), whilst it was used more than 12 h. per day (in this case 15 h.). According to this, the LED-based lighting product lifespan in the best case scenario based on the consumer questionnaire results is the following:

Lb_consumer = hb_consumer∗Yb_consumer∗365 = 15∗5∗365 = 27, 375 h.

In the worst case scenario, LED-based lighting products failed within one year of use (Fig. 6.3), in this case 1 year was considered as the worst case scenario-service-years (Yw = 1), when lighting products were used 0-4 h. per day (Fig. 6.4), in this case was considered 4 h. (hb = 4). Therefore, in the worst case scenario, the product failed after 1 year of use, whilst it was used 0-4 h. per day (in this case 4 h.). According to this, the LED-based lighting product lifespan in the worst case scenario based on the consumer questionnaire results is the following:

Lw_consumer = hw_consumer∗Yw_consumer∗365 = 1∗4∗365 = 1460 h.

In the best case scenario, LED-based lighting products failed after 5 years of use (Fig. 6.5), when lighting products were used more than 12 h. per day (Fig. 6.6), in this case it was considered 15 h. per day (hb = 15) and failure period after 6 years (Yb = 6). According to this, the LED-based lighting product lifespan in the best case scenario based on the manufacturer questionnaire results is the following:

$$L_{b\_manufacturer} = h_{b\_manufacturer} * Y_{b\_manufacturer} * 365 = 15*6*365 = 32850 \text{ h.}$$

In the worst case scenario, LED-based lighting products failed in the first year (Yw = 1) (Fig.6.5), when lighting products were used from 9–12 h per day (hb = 10) per day (Fig. 6.6). According to this, the LED-based lighting product lifespan in the worst case scenario based on the manufacturer questionnaire results is the following:

$$L_{w\_manufacturer} = h_{w\_manufacturer} * Y_{w\_manufacturer} * 365 = 1*10*365 = 3650 \text{ h.}$$

<u>Causes of failure:</u>

According to the survey responses, 68.29% of LED-based lighting products did not fail, but 31.71% failed after consumers had purchased them, as shown in Fig. 6.7.

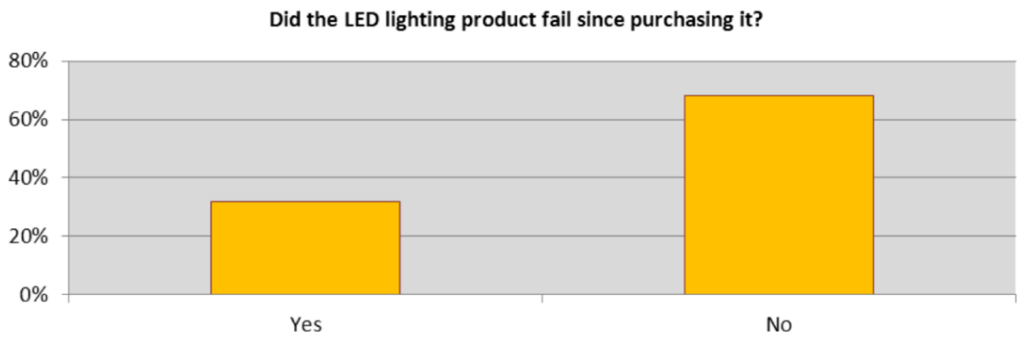


Figure 6.7. LED-based lighting product failure rates.

Amongst the failed LED-based lighting products, consumers stated that LED-based lighting products failed or were replaced because of the following reasons: 1) driver failure (8.33%), 2) LED failure (8.33%), 3) cooling system failure (2.38%), 4) dimmer failure (1.19%), 5) light does not illuminate objects with the desired colour (3.57%), 6) lighting product produced less light then needed (3.57%) and 7) consumers wanted new LED lighting products with a new appearance (1.19%). 71.43% did not know why the products had failed (Fig. 6.8).

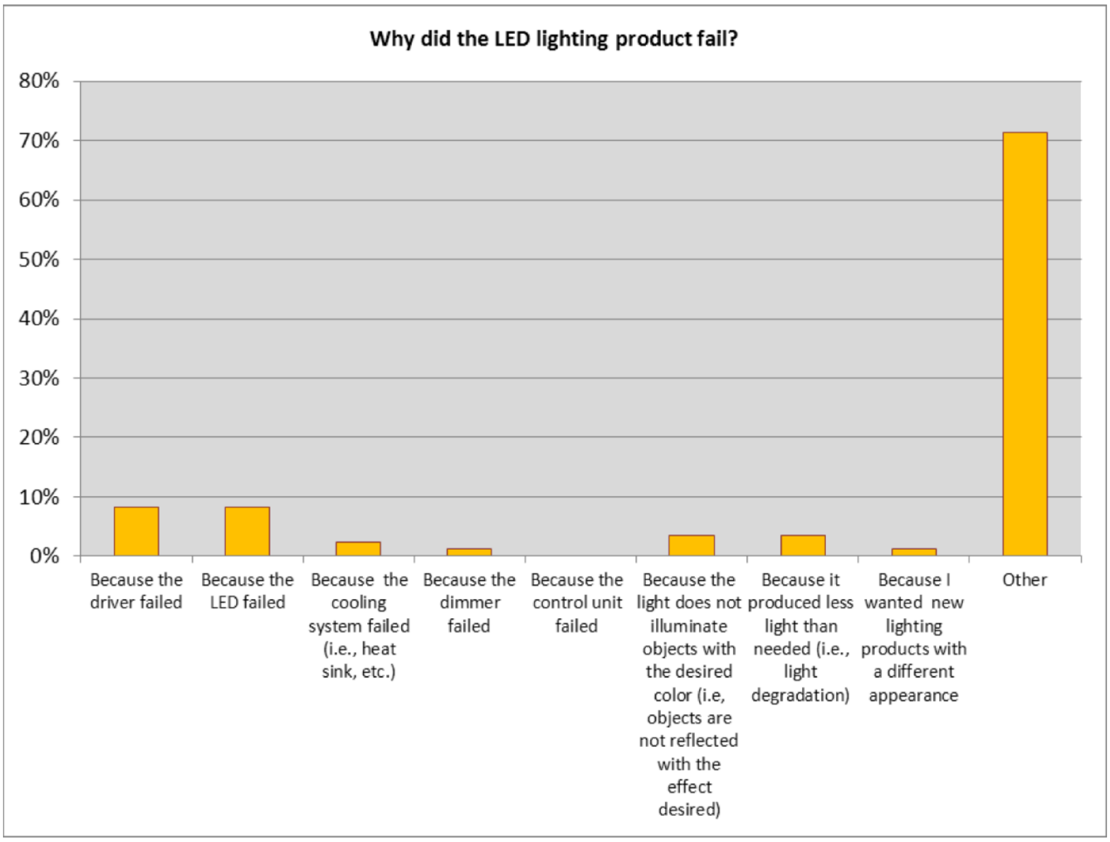


Figure 6.8. Causes of LED-based lighting product failure or replacement – consumers' questionnaire results.

Fig. 6.9 shows the reasons why the LED-based lighting products were returned based on the answers in the manufacturers' questionnaire. The lighting products were returned due to the following reasons: 1) driver failure (42%), 2) LED failure (14%), 3) cooling system failure (2%), 4) control unit failure (6%), 5) less light than needed (light degradation) (6%) and 6) other causes (30%).

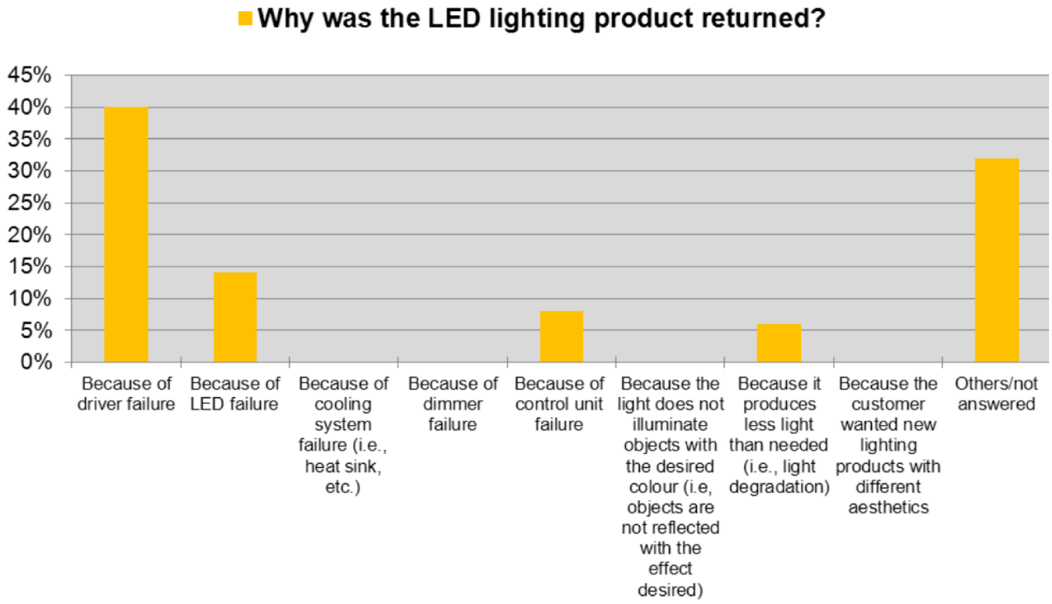


Figure 6.9. Causes of LED-based lighting product failure or substitution – manufacturers' questionnaire results.

6.4 - Discussion

The questionnaires' answers from both types of participants (consumers and manufacturers) have been taken into consideration in the discussion, which is presented below under specific topics:

- *Failure pattern*:

Fig. 6.7 shows that 31.71% of LED-based lighting products purchased by consumers had failed to fulfil their expected function during the time the consumers used the products. Fig. 6.3 and 6.5 shows the highest failure rate was during the first year of use, slowly decreasing each year until the fifth year, and increasing slightly again after the fifth year in the survey of manufacturers (Fig. 6.5). The failure pattern over time resembles the electrical-electronic components 'bathtub' typical lifespan curve (Fig. 6.1), with high failure rates during the first year (early failure period) usually due to manufacturing faults, and low failure rates during the mid-lifespan (spontaneous failure period) of the components. After the fifth year, the failure rate begins to increase again, which resembles the 'wear out period' of the 'bathtub' curve (Fig 6.1), where electronic components begin to fail again due to the natural degradation of components.

- *Causes of failure or replacement of LED-based lighting products:*

According to the survey results (Fig. 6.8 and 6.9), the failure or replacement of the LED-based lighting products was mainly due to the following:

1. Technical failure of driver and Light source (LED), and less frequent failure of control unit and cooling system.
2. Reduction of light quantity and quality output of the lighting product over time below the initial light performance specified by the manufacturer.
3. Need for aesthetic upgrade (especially in consumers' survey answers, Fig. 6.8).

A large number of responses ('other' 71.43% in consumer surveys) indicates that the causes of failure were unknown, especially in the case of consumers (in the manufacturer's questionnaire the 'other' Reponses corresponds to 30%), since consumers might not have the technical knowledge or tools to diagnose the cause of the failure. In the case of manufacturers, the lighting products that failed were sent back to their respective companies by the consumers, usually under warranty. Once in the company, these failed lighting products could be diagnosed and the causes of failure registered in a database for quality control purposes. Therefore, the answers regarding 'causes of failure', provided by the manufacturers' survey should be more reliable than the answers from consumers.

- *Lifespan of LED-based lighting products:*

The total lifespan was calculated based on the average daily usage hours (Fig. 6.4 and 6.6) multiplied by the number of years (Fig. 6.3 and 6.5) until the product fails. Since there was not a clear predominant pattern of usage daily hours (i.e. 34.15% were used for 0–4 h, 26.83% were used for both 5–8 h and 9–12 h, and 12.20% were used for more than 12 h), and there was not a clearly predominant pattern of failure (i.e. products failed in higher % in different years), this study developed a new approach to present the LED-based lighting product lifespans using two scenarios (worst and best case scenarios).

In the consumers' survey, in the worst case scenario, the LED-based lighting products failed after the first year of use (79.31%) and were used 0–4 h (4 h. was considered for the calculation) per day (34.51%), resulting in a lifespan of 1,460 h. On the other hand, when it was considered the best case scenario, the LED-based lighting products failure rates after the third year of use was almost 0% (the fourth and fifth years), and were used more than 12 h. (15 h. was considered for the calculation) per day (12.20%), resulting in a lifespan of 27,375 h.

In the manufacturers' survey, in the worst case scenario, the LED lighting products failed After the first year of use (60%) and were used 9–12 h (10 h was considered for the calculation) per day (46%), resulting in a lifespan of 3,650 h. On the other hand, when it was considered the best case scenario, the LED-based lighting products failure rates after the fifth year was 4%, (6 years was considered for the calculation), and were used more than 6 h. (15 h. was considered for the calculation) per day (12%), resulting in a lifespan of 32,850 h.

Limitations of the study:

The limitations of this study were that the lifespan data obtained from consumers and manufacturers might not be totally accurate because in order to have accurate data, the LED-based lighting products should have been 'tracked' from the moment they were purchased until they failed or were replaced in an individual basis. However, this type of study would need a lot of resources (time and budget). In addition, although consumers were selected as participants, their answers regarding 'why the product failed' could not be trusted completely since they did not have the technical skills and knowledge to diagnose why the LED-based lighting product failed (in case of functional failure). This might explain the high percentage in 'other' category answers, because they did not know why the product had failed. Another limitation is that it was difficult to correlate the year the product failed with the number of hours the product was used, the operating conditions and the cause of the failure, because the answers of the questionnaires did not provide this type of data from each lighting product. Therefore, only averages could be obtained, which did not show the correlations, which could have given more insights about why each individual lighting product failed or was replaced.

Although the data obtained from manufacturers was more reliable, this was mainly based on the lighting products received by the manufacturers under warranty, which were diagnosed, and registered in their databases. This could bias and distort the results because warranties usually last 3-5 years only, so lighting products that fail after 3 years might not have been registered. Furthermore, this data collection method does not account for the lighting products that were replaced because the user wanted a new product with new aesthetics, because only products that need to be replaced (under warranty) due to a functional failure are sent to the company.

Mismatch between consumers and manufacturers surveys' results:

The reason why the consumers and manufacturers surveys' lifespan results differ is due to the differences between how the data was collected. Manufacturers' methods to monitor their lighting products are more systematic and rigorous than the ones used by consumers. This means that they usually keep a record of their lighting products inventory, maintenance and lifespan in databases. On the other hand, consumers have to rely on their memory since they do not use such systems, this may produce answers that do not reflect the reality accurately. In addition, consumers do not usually have the knowledge and skills to diagnose why the lighting product failed, whilst the manufacturers usually have technical staff that can diagnose the cause of failure, which is recorded in the database. With hindsight, consumers should not have been included in the survey, because they may have distorted the results. However, they were included because manufacturers do not usually receive failed lighting products after the warranty period, which does not reflect the reality (i.e. lighting products that last longer may not be recorded). The mismatch of the lifespan-related figures provided from the consumers and manufacturers did not have implications for the research, because both results were taken as a *reference* (not as a definitive value) with another study (CALiPER program, US DOE, 2009b) to estimate the lifespan that was used to inform the LCA-based method in Chapter 5 (Method to assess and compare LED-based lighting products). On the other hand, the causes of end of life provided by the consumers and manufacturers were similar in some cases, although the ones obtained from the manufacturers' survey were considered more to inform the eco-design guidelines because the diagnosis of the manufacturers was supposed to be more reliable.

6.5 - Design and use recommendations to extend the lifespan of LED-based lighting products

LED-based lighting products may fail because of the failure of the LED module, associated electronic components required for the proper functioning of the LED, and mechanical structure of the lighting product. LED-based lighting products will be disposed not only when the LED or other electronic components fail, but also when the mechanical structure of the lighting product fails. In the latter case, the LED-based lighting product electronic components in perfect working conditions are disposed because the lighting product structure was not robust enough. Therefore, attention must be paid to, not only the lifespan of the electronic components, but also to the lifespan of the LED-based lighting product as a whole, including the housing that support and protect the electrical-electronic components contained inside.

The design and use recommendations to extend the lifespan of LED-based lighting products are targeted at:

- *LED-based lighting product developers.*
- *LED-based lighting product end users.*

<u>Design recommendations targeted at LED-based lighting product developers:</u>

The following recommendations are generally applicable for all components of the LED-based lighting products, including driver, LED, dimmer, cooling system and control unit:

(i) Design or select a component which needs little maintenance (UNEP and TU Delft, 2006): the components that need maintenance may be more prone to fail if they are not properly maintained, so designing or selecting a control unit which does not need maintenance will reduce the possibilities of failure due to poor maintenance.

(ii) Use standard components to ensure serviceability (UNEP and TU Delft, 2006): to facilitate replacement of these components in case of failure.

(iii) Provide information about how to upgrade the components (UNEP and TU Delft, 2006). With such information, the lighting product can be upgraded over time with new components, which may avoid replacement.

(iv) Provide information about how to dismantle and repair the components (UNEP and TU Delft, 2006). With such information, failed components can be dismantled and replaced to keep the system functioning.

(v) Provide information about where to obtain spare components (UNEP and TU Delft, 2006): Information about components' references and its suppliers should be provided to facilitate the user to find replacements of failed components. It is advised to use well-known suppliers worldwide to ensure a steady supply over time.

(vi) Select high-quality component brands (UNEP and TU Delft, 2006): Selection of the components from well-known and reliable brands usually will ensure a steady and safe functioning of the electronic components over time (under typical operating conditions). These suppliers usually test, under controlled conditions, the electronic components thoroughly before they go into production, so their behaviour over time can be predicted and estimated.

The following recommendations are only applicable to the driver failure:

(i) Select reliable and suitable capacitors within the driver: Capacitors are usually the cause of driver failures.

(ii) Design or select drivers which can stand voltage and current fluctuations (US DOE, 2009b): Voltage and current fluctuations may cause driver failure.

(iii) Design the lighting product to avoid moisture infiltration in the driver (Philips, 2010): Moisture infiltration in the casing containing the driver may lead to driver failure or early degradation and loss of performance.

(iv) Select high-quality drivers which have been tested to ensure required quality standards (UNEP and TU Delft, 2006): Selection of drivers from well-known and reliable driver suppliers usually will ensure a steady and safe functioning of the driver over time (under typical operating conditions). These suppliers usually test, under controlled conditions, the drivers thoroughly before they go into production, so their behaviour over time can be predicted and estimated.

(v) Drivers should not be assembled in the same casing with the LED, so they do not get affected by the heat emitted by the LED. LEDs installed within the same casing will increase the temperature inside the casing which will make the driver work under higher temperature operating conditions, increasing the risk of failure or premature degradation of the drivers' components leading to performance losses.

The following recommendations are only applicable to the LED failure:

(i) Design LEDs with optimal thermal management (Osram, 2008): The lower the thermal resistance of the LED, the better the thermal properties of the LED become. If heat is dissipated quickly and efficiently, the junction temperature does not increase as rapidly, and as a result, the lifetime of a LED (and the lighting product) will increase.

(ii) Design the lighting product so the LED does not have to operate at high forward LED input current (Chwan, 2012): This reduces the lifespan of the LED.

(iii) Select LEDs that have been manufactured following stable and optimised production processes in order to minimise the risk of spontaneous failure (Osram, 2008): Early failure of LEDs is usually generated by defective materials, and/or deviations in the manufacturing process.

(iv) Select the correct material and layout of the circuit board to increase heat dissipation (Osram, 2008): The selection of the material and the layout of the circuit board will influence the heat dissipation generated by the LED.

(v) Provide additional cooling (Osram, 2008): to ensure that the junction temperature of the LED is always under the optimum operating temperature of the LED.

(vi) Store LEDs in correct conditions: Humidity, moisture, temperature and light radiation can affect the LEDs, therefore dry, protected storage areas should be used.

(vii) Handle LEDs carefully when picking and placing them (Osram, 2008): Although LEDs are not as fragile as other type of light sources such as incandescent bulbs, they are also sensitive to impact and should be handled carefully to avoid problems.

(viii) Select suitable heat distribution systems (active/passive cooling systems): to avoid the junction temperature of the LED rise over the optimum working temperature specified by the LED supplier.

(ix) Design measures for Electro Static Discharge (ESD) Protection (Osram, 2013): LEDs can fail because of electro static discharge, which is why LEDs and the systems that contain them should be shielded for ESD.

(x) Avoid damage or degradation of the encapsulant material covering the LEDs (US DOE, 2009b): The mechanical properties of encapsulants serve a key function, which is to protect the LED from the outside environment. When this encapsulant is damaged, the LED is exposed to environmental external factors such as humidity, moisture temperature and light radiation. All these factors may cause failure of the LED or premature degradation, thus shortening its lifespan.

(xi) Keep junction temperature of LED below 125°C (Chwan, 2012): As a general rule (this may differ depending on supplier) LED junction temperature should be kept below 125°C in order to allow the LED to work in optimal conditions for optimal lifespan. This means that the temperature inside the casing of the LED have to measured, and cooling systems applied if the temperature reaches more than 125°C.

(xii) Design the lighting product to avoid moisture infiltration in the LED (Philips, 2010; US DOE, 2009b): This will be influenced by the encapsulant of the LED, and the design of the casing of the LED within the lighting product. Well sealed lighting products which pass high Ingress Protection (IP) tests will allow the LED to be less exposed and affected by external environmental factors.

(xiii) Avoid damage of the wire bonds that connect the LEDs to the fixture (US DOE, 2009b): Design the lighting product so the wire bonds that connect the LEDs to the lighting product are difficult to break or damage with mechanical external forces or extreme environmental conditions over time.

Recommendations to avoid other reasons of end of life:

- Lighting product does not illuminate the objects with the required light quality (CCT, CRI).

(i) Provide information to users about the light quality emitted by the lighting product, and offer light quality recommendations for each specific lighting application. Customers should have available enough light quality information before they purchase the lighting product, so they can choose the most suitable light quality (CCT, CRI, distribution of light) for their applications.

- Lighting product produces less light than initially required (light output degradation).

(i) The causes of light output degradation are similar to the causes of LED failure stated in 'LED failure' recommendations. The same causes of LED failure can also cause premature degradation and ageing of LEDs, leading to loss of light output. If the loss of light output continues, at some point the light output performance can be under the minimum light output threshold requirements for specific applications, leading to disposal or replacement of the lighting product. For this reason, to avoid this situation lighting product developers have to pay attention to the same design recommendations suggested to mitigate LED failure.

- Preference for new aesthetics (old aesthetics is no longer desired).

(i) Design the lighting product so the aesthetic does not quickly become uninteresting, thus ensuring that the product's aesthetic life is not shorter than its technical lifespan (UNEP and TU Delft, 2006).
(ii) Design the lighting product so it can be aesthetically updated (UNEP and TU Delft, 2006): Lighting products that can change, evolve and update their external aesthetics, can evolve along trends and changes of personal aesthetic preference of users.
(iii) Design a modular lighting product (UNEP and TU Delft, 2006): Modular architecture of lighting products facilitates aesthetic and technical upgrading.
(iv) Design for lighting product (emotional) attachment (Van Nes, 2010).

Overall recommendations for the whole lighting product to extend its lifespan:

(i) Make sure the construction is sound so that it does not become prematurely obsolete in the technical sense. Special methods such as Failure Mode and Effect Analysis (FMEA) can be used for this purpose. Indicate which parts have to be cleaned or maintained in a specific way, and which parts or sub-assemblies have to be inspected often, due to rapid wear.

(ii) Locate the parts which wear relatively quickly close to one another and within easy reach so that components are easy to dismantle for repair or replacement.

(iii) Make the beginning of the wear on parts of the product detectable, so that repair or update can take place on time.

(iv) Try to design the lighting product so all components have the same lifespan, thus avoiding disposal of the product due to one single component failure.

(v) Provide Minimum guaranteed lifetime (Eco-design parameters for Energy-Using Products, 2003 (2003/0172) COD): Long warranties usually increase the lifespan of the lighting product.

(vi) Select high-quality components which have been tested to ensure minimum quality standards.

(vii) Design the lighting product so it needs little maintenance (UNEP and TU Delft, 2006).

Use recommendations targeted at end users:

LED-based lighting products may fail, or end their life prematurely, due to use in extreme operating conditions, for example:

- LED-based lighting products, which are used in very hot environments have a short lifespan.
- Thermal and voltage fluctuations problems which are the main reasons for LED and driver failure.
- Operating conditions under high vibrations levels.

The following recommendations are only applicable to the LED failure:

(i) Avoid operating the lighting product in areas where there are voltage fluctuations of the grid because it may reduce driver lifespan or enhance the possibility of failure (VITO NV, 2009).

The following recommendations are only applicable to the driver failure:

(i) Avoid exposing the lighting product to Electro Static Discharge (ESD) (Philips, 2010).
(ii) Avoid using the lighting product under high vibrations in operative conditions (Philips, 2010).
(iii) Avoid using the lighting product at high temperatures (US DoE, 2009b).
(iv) Avoid impacts during transport, installation and use.
(v) Avoid operating at high duty cycle (Chwan, 2012).

Lighting product does not illuminate the objects with the required light quality (temperature, CRI):

(i) Obtain information about light quality of the lighting product, and select quality according to lighting specific application needs.

Lighting product produces less light than required (light output degradation):

(i) Avoid operative conditions mentioned in the previous sections, which show use recommendation to avoid LED and drivers' failure.
(ii) Follow Instructions about how to install, use and maintain the lighting product in order to minimise its impact on the environment, and to ensure optimal life expectancy (Eco-design parameters for Energy-Using Products, 2003 (2003/0172) COD).
(iii) Keep clean and maintain the optical elements periodically.

Preference for new aesthetics (i.e. old aesthetics is no longer desired):

(i) Choose lighting products which have a long-lasting aesthetic not affected by fashion.
(ii) Choose lighting products which can be updated aesthetically.

Chapter 7: Approach to eco-design LED-based lighting products

This chapter illustrates a descriptive model (section 7.1) of the eco-design process followed in the case study. The model has been used as a reference to create an approach (section 7.2) to eco-design LED-based lighting products.

7.1 - Descriptive model of eco-design process from the case study

The process to eco-design LED-based lighting products (case study) has been modelled (Fig. 7.1) based on: The design process stages (PDS, concept design, embodiment design), the tools, methods and techniques used (EDG, EDG-CH) in the process, when and how these were applied during the design process.

The descriptive eco-design process model begins with a briefing, which is materialised into a finished product at the end of the process. The process has been shaped as a funnel because at the beginning of the process there were few constraints and any design decision was possible so the design space (or design possibilities) was extensive. However, as the process continues the lighting product is defined in more detail, and the design possibilities are reduced.

The modelling of the process was framed in several stages according to the traditional design process stages process: PDS, concept design, embodiment design, detail design and testing-analysis. These stages are usually determined by the definition of the product. In each of these design stages, different tools, methods and techniques were applied in order to support the product designers' eco-design decision-making processes. In any design process the product is subject to a continuous analysis and synthesis process, where the product is analysed at each stage to define it (i.e. synthesis) and improve it in more detail. In eco-design processes, one key dimension of the analysis is the assessment of the environmental impact of each design decision that is why eco-design tools, methods and techniques need to be applied during the process (described in detail in chapter 4).

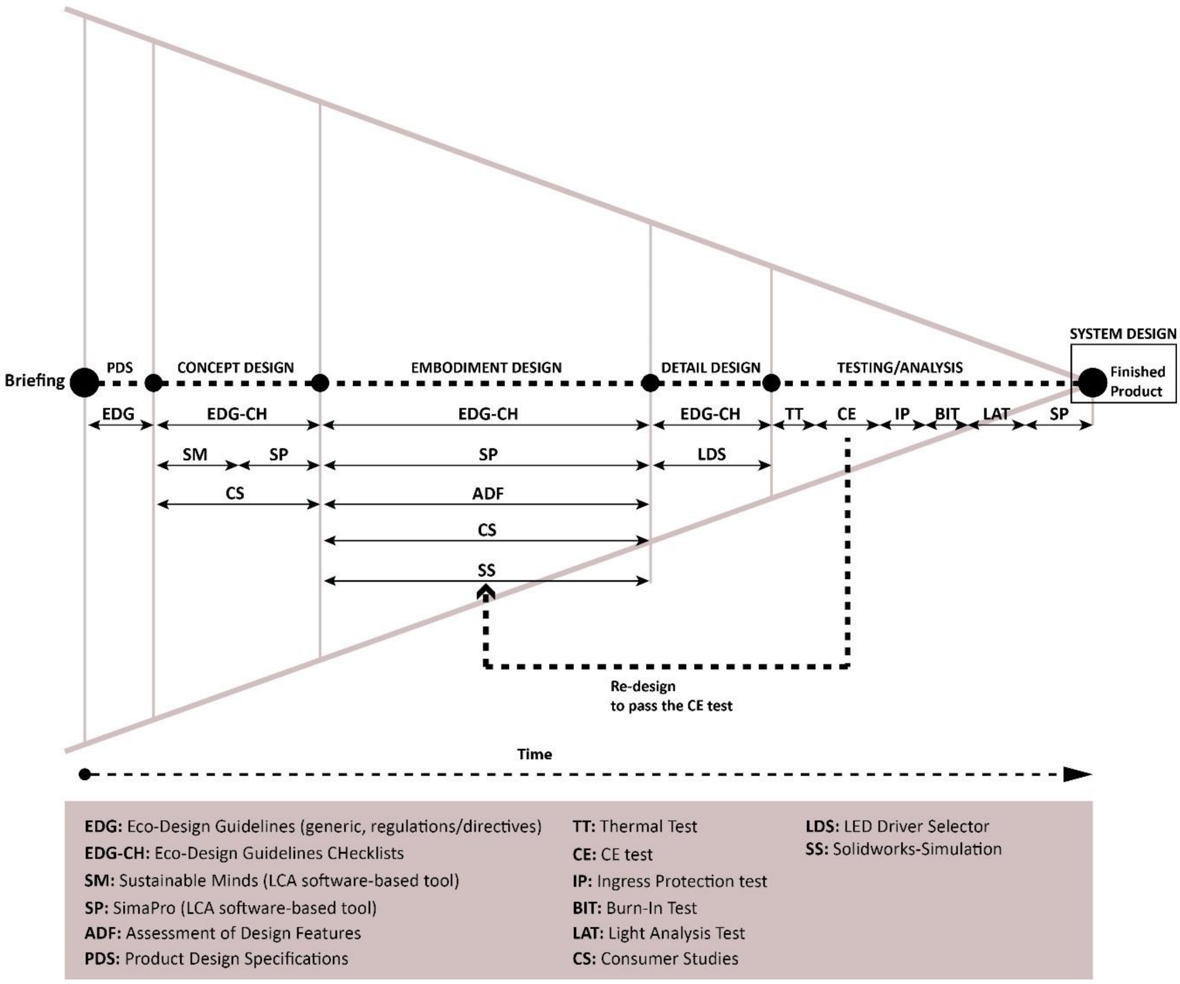


Figure 7.1. Descriptive model of eco-design process of case study.

In the descriptive model shown (Fig. 7.1), several tools, methods and techniques were applied in each design process stage as follows: In the Product Design Specifications (PDS) stage, generic Eco-Design Guidelines (EDG), and eco-design guidelines derived from regulations and directives were applied. In the concept design stage, Eco-Design Guidelines-CHecklists (EDG-CH) were applied, which consisted of using the eco-design guidelines as checklist in each design iteration to try to achieve as many as possible. In addition, it was used two LCA-based software tools (Sustainable Minds and Simapro). Sustainable Minds (SM) was used at the beginning of the process when the product was less defined, and different concepts, materials or manufacturing processes had to be assessed. SimaPro (SP) was used at the later stage of the design concept stage, when an early prototype (final concept) was defined. Simapro was used to provide information about the lifecycle stages and components with the highest impact, this information could be used to ascertain which the most important (priority areas) life cycle stages and components to eco-redesign were. In the next stage (embodiment design stage), Eco-

Design Guidelines Checklists (EDG-CH) were used and one LCA-based software tool (Simapro) was applied. It was also applied the Assessment of Design Features (ADF) method to assess the lighting product design features in order to reduce the environmental impact. Whilst using Simapro can help to compare the environmental impact of different versions of the final concept, and indicate the areas (life cycle stages and components) where further improvement can be made to reduce the environmental impact, LCA-based software tools (e.g. Simapro) alone cannot assess the environmental impact of the lighting product completely. For example, they cannot assess how easy or difficult is to dismantle a lighting product to facilitate repair or recycling, the robustness of a joint, or the light control, to name a few design features. All these design features affect the total environmental impact of the lighting product, and during the embodiment design stage these have to be assessed too. In the detail design stage Eco-Design Checklists (EDG-CH) were applied to make sure the final decisions regarding selection of components and finishes were informed by eco-design guidelines recommendations, and it was used the LED driver selector (LDS) to ensure an optimum match between the LED and the LED-driver selected to save energy. In the final stage (testing and analysis), several tests: Thermal Test (TT), CE mark test (CE), Ingress Protection test (IP), Burn In Test (BIT), Light Analysis Test (LAT), and LCA with SimaPro (SP) were conducted to ensure the reliability and durability of the lighting product. Some of these tests, such as the CE test (CE) are compulsory, and others such as the Light Analysis Test (LAT) are necessary to provide the lighting product performance information to inform the final LCA of the lighting product with SimaPro (SP), and to offer photometric files to help consumers match the light output of the lighting product with the lighting application. The detailed LCA-based method to assess and compare LED-based lighting products using SimaPro (SP) is explained in chapter 5. Consumer Studies (CS) were conducted during the concept and embodiment design stages to ensure that the eco-design features implemented in the lighting product were demanded and wished by the final consumer. This is crucial because eco-lighting products, need to appeal to consumers so that they purchase eco-lighting products instead of non-eco lighting products. If the lighting product is not purchased, all the effort in trying to reduce the environmental impact will not have the desired impact in the market.

Once the LED-based lighting *product* has been eco-designed, it is possible to reduce further the environmental impact of the lighting product, by designing a *system* around the lighting product to contribute in extending the lifespan of the lighting product and the materials contained in it (Fig. 7.1). One of the problems of trying to reduce the environmental impact of lighting products is that, although manufacturers and product designers can control the environmental impact caused at the manufacturing stage, they cannot control the total impact caused during the use and end of life stages, because they cannot prescribe and predict how the user will use and dispose the lighting product. For example, product designers can design an energy-efficient lighting product, but they cannot control the correct use of the lighting product to reduce the energy used and also to extend its lifespan. In addition, they cannot control how the lighting product will be disposed, which means that easy to dismantle fully recyclable lighting products may end up in the domestic bin. That is why in order to gain some control about how the lighting product will be used and disposed, a system was designed to incentivise and facilitate specific user behaviour that could reduce further the environmental impact of the lighting product. The system (described in section 4.4: Case study: System designed around the lighting product), focuses on extending the lifespan of the lighting product and the materials contained in it by facilitating repair, re-use and recycling, and it is based on the following features:

- It provides information in the website of the manufacturer about: 1) how to dismantle the lighting product, 2) the supplier of each component and its reference in case of replacement, and 3) where to recycle the lighting product.
- It offers long warranties.
- It allows the possibility to upgrade the lighting product (i.e. components such as LEDs, drivers, modules) by the manufacturer.
- It offers discounts for new lighting products from the manufacturer if the old lighting product bought to the manufacturer is returned.
- It offers instructions to the end-user of how to use the lighting product to make it last longer.

The eco-design process of the packaging used for the lighting product developed has been described and examined in section 4.3 (case study: packaging of LED-based lighting product), but has not been modelled in the descriptive model of eco-design process of case study (Fig. 7.1). The descriptive model can be seen more detail (scaled) in Appendix 7.1.

7.2 - Approach

The descriptive eco-design process model showed in Fig. 7.1 is a model of the process followed in the case study, which describes the stages followed, and the tools, methods and techniques used at each stage. This model and the process conducted provided many insights about areas of the model that could be improved, which were used to inform the new approach proposed (Fig. 7.2). The new approach has been improved, in comparison with the descriptive model (Fig. 7.1), in the following areas:

1) *Design process stages*: The design process has been divided in four main stages (PDS, concept design, detail design and testing-analysis) instead of five, because the boundaries between embodiment design and detail design are sometimes difficult to distinguish. As it has been shown in chapter 2 (literature review), many eco-design methods do not differentiate them, and use one (embodiment design) or the other (detail design) to define the design stage after the concept design stage. Although it has been separated the detail design stage and the testing-analysis stage, it is common that basic general tests (e.g. basic disassembly test, basic thermal test) are conducted during the detail design stage to verify some design features.

2) *Application of tools, method and techniques:* The application of Sustainable Minds (SM) in the concept design stage was substituted by the use of a CAD-LCA tool such as Solidworks-Sustainability which allows the assessment of the environmental impact of design decisions (e.g. change of materials, change of geometry) simultaneously with no extra time-effort. This tool allows to conduct simple assessments, like Sustainable Minds, but without any additional effort-time, because once the product is modelled in CAD there is no need to input the information into another software. In addition, the information of the product is very accurate because it is based on the Bill of Materials (BoM) from the CAD model. The use of SimaPro (SP) at the concept design stage is not very suitable because the lighting product is not defined enough to have the type of detailed information required by Simapro, and this tool is not flexible and fast enough to adapt to the concept design stage where continuous drastic design changes occur.

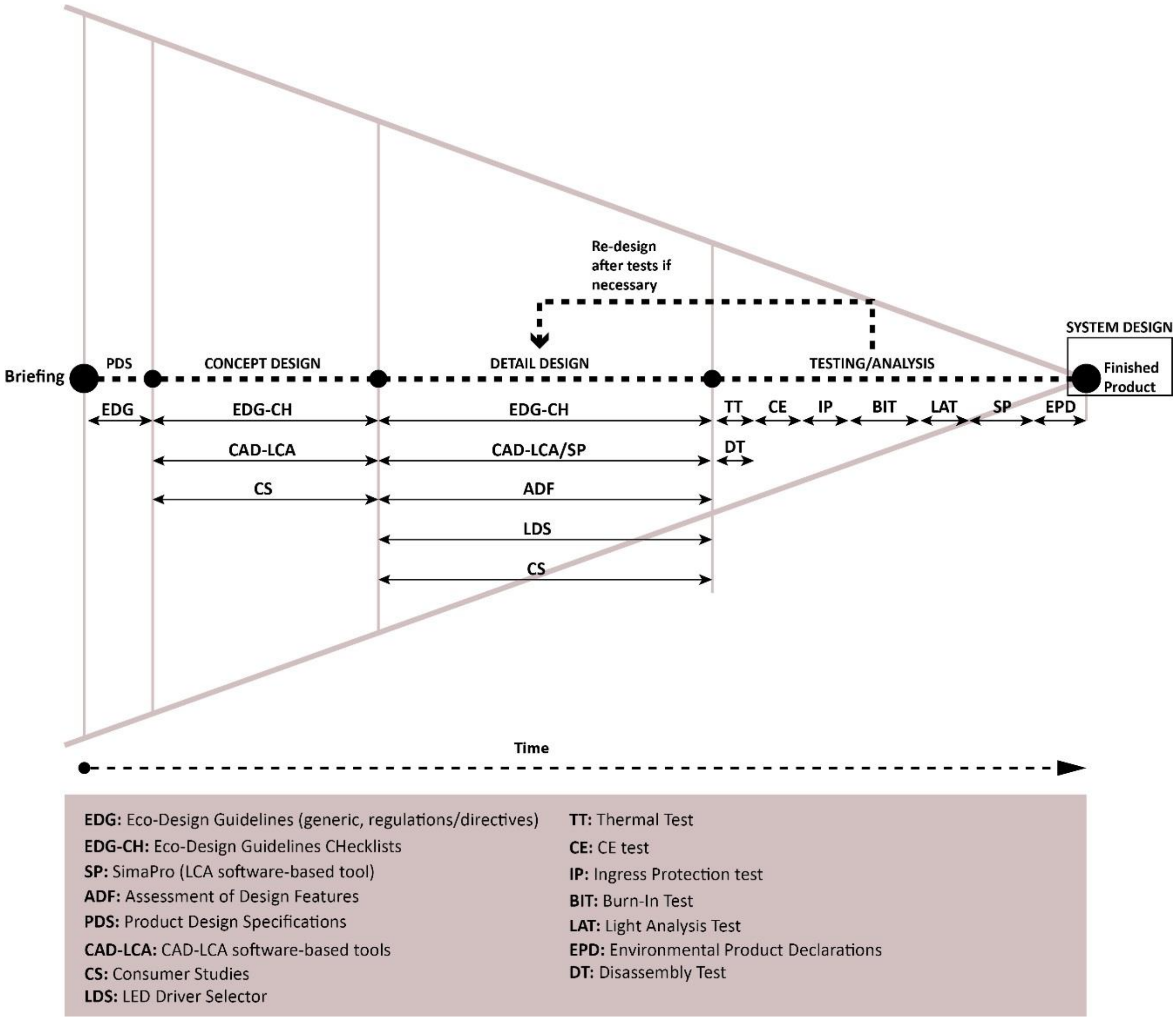


Figure 7.2. Approach to eco-design LED-based lighting products

In the new approach, at the detail design stage, Simapro (SP) was replaced by a CAD-LCA tool because it allows, as it has been mentioned earlier, the assessment (and comparison) of design decisions simultaneously, whilst Simapro (SP) requires to input all the information about the lighting product every time a design decision is taken. In addition, Simapro is time-consuming to use, requires specialised expertise, and is not flexible enough to be used if design decisions are taken often. For this reason, Simapro is more suitable at the end of the design process, or, sometimes, at the detail design stage only if a defined prototype is available. At the testing-analysis stage, in addition to the tests shown in the descriptive model (Fig.7.1), it has been added an additional test to obtain an eco-label or similar (i.e. Environmental Product Declarations: EPD) to provide information about the environmental profile of the lighting product which can be communicated to consumers. During the testing-analysis stage, failure to pass any of the tests may lead to re-design of the lighting product, which means that the lighting product has to pass through the detail design stage again. An additional test (disassembly test) has also been added in the testing-analysis stage to ensure that the lighting product can be dismantled fast and easily to facilitate repair, upgrade or recycling.

The approach can be seen more detail (scaled) in Appendix 7.2.

Chapter 8: Conclusions and future research

This chapter summarises the contributions to knowledge of this research (section 8.1) and highlight potential areas for further study (section 8.2) related with this research.

8.1 - Contribution to knowledge

This research has made several contributions to knowledge in the area of 'eco-design of LED-based lighting products'. The contributions cover several topics that needed to be researched to increase the understanding of how to reduce the environmental impact of LED-based lighting products: 1) Product-related features that influence the environmental impact of LED-based lighting products at each product life cycle stage; 2) Lifespan and causes of end of life of LED-based lighting products; 3) Design and use recommendations to extend the lifespan of LED-based lighting products; 4) Method to assess and compare the full environmental impact of LED-based lighting products; 5) Approach to eco-design LED-based lighting products.

The eco-design of LED-based lighting products has not been researched in previous studies, and therefore the understanding of the areas investigated in this research (mentioned above) represent a novel contribution to knowledge to this field. Explained below are the specific contributions to knowledge related with each of the topics mentioned above:

<u>Product-related features that influence the environmental impact of LED-based lighting products at each product life cycle stage:</u>

The key product-related features that influence the environmental impact of LED-based lighting products are: Quantity and type of materials used, quantity and type of manufacturing processes used to shape and finish the materials, power consumption, disassembly, reliability, volume, maintenance, technical and aesthetical upgrade. Each of these is explained below:

<u>Quantity and type of materials:</u>

The amount of material used and its quality have a major influence in the total impact. More material used means higher resources and energy used for its extraction and refinement, which means higher impact. The quality or type of material used is also key. The selection of materials affects the manufacturing lighting product life cycle stage, which is one of the stages that can be controlled totally by the manufacturer-product designer.

Quantity and type of manufacturing processes:

Materials are shaped and (sometimes) finished to produce components, which are then assembled to form parts, which are then assembled into products. All these activities need manufacturing processes. The amount of manufacturing processes used during the manufacturing of a lighting product, and the type of these will influence the environmental impact of the lighting product. The selection of manufacturing processes affects the manufacturing lighting product life cycle stage, which is one of the stages that can be controlled totally by the manufacturer-product designer.

Power consumption:

The energy used to power the lighting product during the use stage also influence the total impact of the lighting product. LED-based lighting products are energy-dependent products, and as such, the highest impact is usually allocated in the use stage, due to the energy consumed during the use of the product. This design feature (i.e. power consumption) affects the use stage of the lighting product life cycle, which is one of the stages that is not totally under the control of the manufacturer-product designer.

Disassembly:

The easiness of disassembly of a lighting product is also another issue that affect the impact. LED-based lighting products that are easy to disassemble are easier to repair, upgrade and recycle. Ease of disassembly is determined but how easy or difficult is to dismantle a product, and how long it takes to dismantle it. This issue affects the use and end of life stages of the lighting product life cycle, which are the two stages that are not totally under the control of the manufacturer-product designer. Easy disassembly can conflict with CE safety standards as it was discovered in this research, so LED-based lighting products have to be easy to dismantle whilst complying with the CE safety standards.

Reliability:

The reliability of a LED-based lighting product and its components affect the lifespan of the lighting product, and hence its environmental impact. Lighting products with reliable (and thoroughly tested) components and systems will be less prone to failure and hence more durable. This issue affects the use stage of the lighting product life cycle, which is one of the stages that are not totally under the control of the manufacturer-product designer.

Volume and weight:

The volume and weight of a LED-based lighting product will affect the volume needed during the distribution of the product to the consumer. Lighting products with higher volume and weight will have higher environmental impact during distribution. This issue affects the distribution stage of the lighting product life cycle, which is one of the stages under the control of the manufacturer-product designer.

Maintenance:

The maintenance of the lighting product can affect its lifespan, and hence affecting its environmental impact. Lighting products that can be repaired and maintained will last longer and will perform better during their useful life. This issue affects the use stage of the lighting product life cycle, which is one of the stages that is not totally under the control of the manufacturer-product designer.

Technical and aesthetical upgrade:

Technical and aesthetical upgrade of the lighting product can affect its lifespan, and hence it affects its environmental impact. Lighting products that can be upgraded technically (e.g. new functions), or aesthetically (e.g. new shapes, colours), will be able to evolve with the consumer changing preferences, and last longer. This issue affects the use stage of the lighting product life cycle, which is one of the stages that are not totally under the control of the manufacturer-product designer.

Lifespan and causes of end of life of LED-based lighting products, and design and use recommendations to extend the lifespan of LED-based lighting products:

According to the author's literature review there is no study that has investigated the lifespan and causes of end of life of LED-based lighting products to inform design (for product designers) and use (for end users) recommendations to extend the lifespan of LED-based lighting products.

Lifespan of LED-based lighting products

The lifespan was obtained from two surveys (one for consumers of LED-based lighting products and one for manufacturers of LED-based lighting products). The results of each survey considered two scenarios: best and worst case scenarios. In the consumers' survey (best case scenario) the average lifespan was 16,425 h. In the best case scenario lighting products failed after 3 years of use and were used 15 h per day, and in the consumers' survey (worst case scenario), the average lifespan was 1,460 h. In the worst case scenario lighting products failed after one year of use and were used 4 h per day.
In the manufacturers' survey (best case scenario) the average lifespan was 32,850 h. In the best case scenario lighting products failed after 5 years of use, and were used 15 h per day. In the manufacturers' survey (worst case scenario) the average lifespan was 3,650 h. In the worst case scenario lighting products failed after one year of use and were used 10 h per day.

Causes of end of life of LED-based lighting products?

The main causes (in order of frequency) of end of life of LED-based lighting products revealed from the manufacturers' and consumers' survey were: Manufacturer's survey: 1) driver failure, 2) LED failure, 3) control unit failure, 4) light output below required thresholds. Consumers' survey: 1) driver failure, 2) LED failure, 3) light output below required thresholds.

Design and use recommendations to extend the lifespan of LED-based lighting products:

The design and use recommendations to extend the lifespan of LED-based lighting products are targeted at: LED-based lighting product developers (design recommendations), and LED-based lighting product end users (use recommendations). The reason why there are recommendations for product designers and users is because the lifespan of LED-based lighting products is influenced by the design of the lighting product and also by the operating conditions (i.e. how and where it is used). Product designers have a limited control about how the lighting product will be used, despite trying to 'script' in the product a specific type of user behaviour. Therefore, use recommendations have to be provided too to have some control about how the LED-based lighting product should be used to extend their lifespan.

The design and use recommendations have listed below:

<u>Design recommendations targeted at LED-based lighting product developers:</u>

The following recommendations are generally applicable for all components of the LED-based lighting products, including driver, LED, dimmer, cooling system and control unit:

1. Design or select a component which needs little maintenance (UNEP and TU Delft, 2006): the components that need maintenance may be more prone to fail if they are not properly maintained, so designing or selecting a control unit which does not need maintenance will reduce the possibilities of failure due to poor maintenance.
2. Use standard components to ensure serviceability (UNEP and TU Delft, 2006): to facilitate replacement of these components in case of failure.
3. Provide information about how to upgrade the components (UNEP and TU Delft, 2006). With such information, the lighting product can be upgraded over time with new components, which may avoid replacement.
4. Provide information about how to dismantle and repair the components (UNEP and TU Delft, 2006). With such information, failed components can be dismantled and replaced to keep the system functioning.
5. Provide information about where to obtain spare components (UNEP and TU Delft, 2006): Information about components' references and its suppliers should be provided to facilitate the user to find replacements of failed components. It is advised to use well-known suppliers worldwide to ensure a steady supply over time.
6. Select high-quality component brands (UNEP and TU Delft, 2006): Selection of the components from well-known and reliable brands usually will ensure a steady and safe functioning of the electronic components over time (under typical operating

conditions). These suppliers usually test the electronic components thoroughly under controlled conditions before they go into production, so their behaviour over time can be predicted and estimated.

The following recommendations are only applicable to the driver failure:

1. Select reliable and suitable capacitors within the driver: Capacitors are usually the cause of driver failures.
2. Design or select drivers which can stand voltage and current fluctuations (US DOE, 2009b): Voltage and current fluctuations may cause driver failure.
3. Design the lighting product to avoid moisture infiltration in the driver (Philips, 2010): Moisture infiltration in the casing containing the driver may lead to driver failure or early degradation and loss of performance.
4. Select high-quality drivers which have been tested to ensure required quality standards (UNEP and TU Delft, 2006): Selection of drivers from well-known and reliable driver suppliers will usually ensure a steady and safe functioning of the driver over time (under typical operating conditions). These suppliers usually test the drivers thoroughly under controlled conditions before they go into production, so their behaviour over time can be predicted and estimated.
5. Drivers should not be assembled in the same casing with the LED, so they do not get affected by the heat emitted by the LED. LEDs installed within the same casing will increase the temperature inside the casing which will make the driver work under higher temperature operating conditions, increasing the risk of failure or premature degradation of the drivers' components leading to performance losses.

The following recommendations are only applicable to the LED failure:

1. Design LEDs with optimal thermal management (Osram, 2008): The lower the thermal resistance of the LED, the better the thermal properties of the LED become. If heat is dissipated quickly and efficiently, the junction temperature does not increase as rapidly, and as a result, the lifetime of a LED (and the lighting product) will increase.

2. Design the lighting product so the LED does not have to operate at high forward LED input current (Chwan, 2012): This reduces the lifespan of the LED.
3. Select LEDs that have been manufactured following stable and optimised production processes in order to minimise the risk of spontaneous failure (Osram, 2008): Early failure of LEDs is usually generated by defective materials, and/or deviations in the manufacturing process.
4. Select the correct material and layout of the circuit board to increase heat dissipation (Osram, 2008): The selection of the material and the layout of the circuit board will influence the heat dissipation generated by the LED.
5. Provide additional cooling (Osram, 2008): to ensure that the junction temperature of the LED is always under the optimum operating temperature of the LED.
6. Store LEDs in correct conditions: Humidity, moisture, temperature and light radiation can affect the LEDs, therefore dry, protected storage areas should be used.
7. Handle LEDs carefully when picking and placing them (Osram, 2008): Although LEDs are not as fragile as other type of light sources such as incandescent bulbs, they are also sensitive to impact and should be handled carefully to avoid problems.
8. Select suitable heat distribution systems (active/passive cooling systems): to avoid the junction temperature of the LED rise over the optimum working temperature specified by the LED supplier.
9. Design measures for Electro Static Discharge (ESD) Protection (Osram, 2013): LEDs can fail because of electro static discharge, which is why LEDs and the systems that contain them should be shielded for ESD.
10. Avoid damage or degradation of the encapsulant material covering the LEDs (US DOE, 2009b): The mechanical properties of encapsulants serve a key function, which is to protect the LED from the outside environment. When this encapsulant is damaged, the LED is exposed to environmental external factors such as humidity, moisture temperature and light radiation. All these factors may cause failure of the LED or premature degradation, thus shortening its lifespan.

11. Keep junction temperature of LED below 125°C (Chwan, 2012): As a general rule (this may differ depending on supplier) LED junction temperature should be kept below 125°C in order to allow the LED to work in optimal conditions for optimal lifespan. This means that the temperature inside the casing of the LED have to measured, and cooling systems applied if the temperature reaches more than 125°C.
12. Design the lighting product to avoid moisture infiltration in the LED (Philips, 2010; US DOE, 2009b): This will be influenced by the encapsulant of the LED, and the design of the casing of the LED within the lighting product. Well sealed lighting products which pass high Ingress Protection (IP) tests will allow the LED to be less exposed and affected by external environmental factors.
13. Avoid damage of the wire bonds that connect the LEDs to the fixture (US DOE, 2009b): Design the lighting product so the wire bonds that connect the LEDs to the lighting product are difficult to break or damage with mechanical external forces or extreme environmental conditions over time.

Recommendations to avoid other reasons of end of life:

- Lighting product does not illuminate the objects with the required light quality (CCT, CRI).

1. Provide information to users about the light quality emitted by the lighting product, and offer light quality recommendations for each specific lighting application. Customers should have available enough light quality information before they purchase the lighting product, so they can choose the most suitable light quality (CCT, CRI, distribution of light) for their applications.

- Lighting product produces less light than initially required (light output degradation).

1. The causes of light output degradation are similar to the causes of LED failure stated in 'LED failure' recommendations. The same causes of LED failure can also cause premature degradation and ageing of LEDs, leading to loss of light output. If the loss of light output continues, at some point the light output performance

can be under the minimum light output threshold requirements for specific applications, leading to disposal or replacement of the lighting product. For this reason, to avoid this situation lighting product developers have to pay attention to the same design recommendations suggested to mitigate LED failure.

- Preference for new aesthetics (old aesthetics is no longer desired).

    1. Design the lighting product so the aesthetic does not quickly become uninteresting, thus ensuring that the product's aesthetic life is not shorter than its technical lifespan (UNEP and TU Delft, 2006).
    2. Design the lighting product so it can be aesthetically updated (UNEP and TU Delft, 2006): Lighting products that can change, evolve and update their external aesthetics, can evolve along trends and changes of personal aesthetic preference of users.
    3. Design a modular lighting product (UNEP and TU Delft, 2006): Modular architecture of lighting products facilitates aesthetic and technical upgrading.
    4. Design for lighting product (emotional) attachment (Van Nes, 2010).

Overall recommendations for the whole lighting product to extend its lifespan:

1. Make sure the construction is sound so that it does not become prematurely obsolete in the technical sense. Special methods such as Failure Mode and Effect Analysis (FMEA) can be used for this purpose. Indicate which parts have to be cleaned or maintained in a specific way, and which parts or sub-assemblies have to be inspected often, due to rapid wear.
2. Locate the parts which wear relatively quickly close to one another and within easy reach so that components are easy to dismantle for repair or replacement.
3. Make the beginning of the wear on parts of the product detectable, so that repair or update can take place on time.
4. Try to design the lighting product so all components have the same lifespan, thus avoiding disposal of the product due to one single component failure.

5. Provide Minimum guaranteed lifetime (Eco-design parameters for Energy-Using Products, 2003 (2003/0172) COD): Long warranties usually increase the lifespan of the lighting product.
6. Select high-quality components which have been tested to ensure minimum quality standards.
7. Design the lighting product so it needs little maintenance (UNEP and TU Delft, 2006).

Use recommendations targeted at end users:

LED-based lighting products may fail, or end their life prematurely, due to use in extreme operating conditions, for example:

- LED-based lighting products, which are used in very hot environments have a short lifespan.
- Thermal and voltage fluctuations problems which are the main reasons for LED and driver failure.
- Operating conditions under high vibrations levels.

The following recommendations are only applicable to the LED failure:

1. Avoid operating the lighting product in areas where there are voltage fluctuations of the grid because it may reduce driver lifespan or enhance the possibility of failure (VITO NV, 2009).

The following recommendations are only applicable to the driver failure:

1. Avoid exposing the lighting product to Electro Static Discharge (ESD) (Philips, 2010).
2. Avoid using the lighting product under high vibrations in operative conditions (Philips, 2010).
3. Avoid using the lighting product at high temperatures (US DoE, 2009b).
4. Avoid impacts during transport, installation and use.
5. Avoid operating at high duty cycle (Chwan, 2012).

Lighting product does not illuminate the objects with the required light quality (temperature, CRI):

1. Obtain information about light quality of the lighting product, and select quality according to lighting specific application needs.

Lighting product produces less light than required (light output degradation):

1. Avoid operative conditions mentioned in the previous sections, which show use recommendation to avoid LED and drivers' failure.
2. Follow Instructions about how to install, use and maintain the lighting product in order to minimise its impact on the environment, and to ensure optimal life expectancy (Eco-design parameters for Energy-Using Products, 2003 (2003/0172) COD).
3. Clean and maintain the optical elements periodically.

Preference for new aesthetics (i.e. old aesthetics is no longer desired):

1. Select lighting products which have a long-lasting aesthetic not affected by fashion.
2. Select lighting products which can be updated aesthetically.

Method to assess and compare the full environmental impact of LED-based lighting products:

No comparative environmental impact assessment of LED-based lighting products has been conducted to date according to the author's literature review. Thus, this method (which is demonstrated in detail in chapter 5) presents an original contribution to knowledge. Although the comparative assessment was demonstrated with two specific lighting products in chapter 5, this method can be applied for the assessment and comparison of eco-design of LED-based lighting products in general.

The method followed is based on the LCA method but with specific considerations to assess and compare LED-based lighting products. The method is divided in the typical stages of the LCA method: Goal and scope definition, inventory analysis, impact assessment and interpretation. The eco-design tools necessary to conduct the assessment are the LCA-based software tool Simapro and the database Ecoinvent. It is advisable to use the latest version available of the software and database to obtain more accurate results.

The key issues that were studied in this LCA-based method were the functional unit, the scenarios assumed, and the Life Cycle Impact Assessment (LCIA) method selected, which are explained below:

<u>Functional unit:</u>
The functional unit that should be used is the luminous flux (i.e. light quantity) produced by the lighting product because it represents clearly the function of the lighting product. However, it should be noted that since the function of the lighting product is to produce a specific quantity and quality of light for a period of time, the light quality should also be considered and specified in the functional unit. The reason why it has not been considered in the demonstration of the method is because it is not yet understood how different Colour Correlated Temperature (CCT) and Colour Rendering Index (CRI) affect the energy consumption, and therefore, it is difficult to determine exactly what the energy consumption of each lighting product based on its CCT and CRI is. Ideally, the lighting products, to be assessed and compared, should provide the same luminous flux (amount of light), and the same CCT and Colour Rendering Index (CRI) (quality of light) to do an objective comparative. The period of time considered in the comparative assessment can be selected based on different scenarios (as explained below: Scenarios). However, it is very important to highlight that it is not recommended to consider different lifespans for each lighting product (e.g. one will last 40,000 h and the other 15,000 h) in the assessment without factual lifespan data of each of them. As considering different lifespan can cause drastic differences in terms of environmental impact, due to the fact that the use stage is the highest product life cycle stage by far in this category of products. Therefore, the comparative assessment results would not be objective or reliable.

Scenarios:

Scenarios are used to check the sensitivity of the results and also to understand what would be the total impact and the impact per life cycle stage of the lighting product if it was assumed different scenarios. The method used and demonstrated in this research assumed a base-case scenario as the most probable scenario. In addition to this, it was assumed several additional scenarios to reflect possible lifecycles of the lighting product. The scenarios focused on different possible: 1) Lifespan of the lighting product, 2) Countries (and hence electricity mixes) where it will be used, 3) Countries where it will be distributed, and 4) End of life scenarios. Out of these scenarios, scenarios about possible lifespan should always be conducted, because they affect the use stage, and the use stage is the lifecycle stage with the highest impact by far. In terms of lifespan, possible scenarios with three lifespans should be considered: A scenario where it is assumed that the lighting product lasts 1,000 h. due to manufacturing faults failure; another scenario where it lasts 15,000 h. which assumes a random failure or replacement, and another scenario of 40,000 h. which assumes the lighting product will last until failure due to natural degradation of components. Other additional scenarios can assume the use of different electricity mixes which are usually dependent on the country where the lighting product is used. Alternatively, the marketing of the lighting product in different countries, which will cause different impact during the distribution life stage, could be considered. Finally, different scenarios have to assume possible end of life scenarios, where the lighting product is disposed in domestic bins or in recycling centres.

LCIA method selected:

Although the eco-indicator 99 LCIA method was selected in the demonstration of the method in chapter 5, it is recommended to use ReCiPe (H) V1.12 LCIA method, since this is the updated version of Eco-indicator 99, which is going to be discontinued. ReCiPe is a very suitable and versatile LCIA method because it allows the provision of results of the assessment in endpoint and midpoint indicators, which is very useful because it allows the delivery of results in endpoint indicators, which are easier to interpret and understand by product designers, and also in midpoint indicators, which are more suitable and meaningful for environmental experts (i.e. midpoint indicators). Environmental experts usually prefer to use midpoint indicators to obtain more transparent results which are free of interpretation through weighting mechanisms.

Hierarchist version (H) is recommended as this is the consensus model, and the one used by default, and in the method followed.

General conclusions about the environmental impact of LED-based lighting products:
After using this method, it has been concluded that the life cycle stage with the highest impact of the LED-based lighting products assessed was the use stage, followed by the manufacturing, end of life and distribution stages. This suggests that the eco-design efforts to reduce the environmental impact of these LED-based lighting products have to be focused on: 1) The use stage, 2) The manufacturing stage, 3) The end of life stage and 4) The distribution stage, and these conclusions can be applied to other LED-based lighting products in general. Therefore, the main eco-design strategies to take into account in reducing the impact of LED-based lighting products is to reduce the energy consumed during the use stage, and this can be achieved by several eco-design strategies: Increasing the luminous efficacy (lm/W), using dimmers, and using smart light controls (e.g. occupancy and light sensors). The luminous efficacy is very dependent of the luminous efficacy of the light source used, the efficiency of the driver (determined mainly by the power factor) and also on the Light Output Ratio (LOR) of the lighting product. Light control also affects the impact of the use stage because lighting products that can control the light intensity and direction of the light can save energy, and hence reduce their impact. In addition, they are also more convenient for the end user.

Approach to eco-design LED-based lighting products:

Eco-design approaches to eco-design LED-based lighting products are not available, so product designers of LED-based lighting products have to rely on the available eco-design methods to design generic products, which do not take into account the particular characteristics of this category of products. It is probable that some companies (e.g. Philips) have developed their own in-house approaches to eco-design LED lighting products but this information has not been disclosed to the public outside their companies so they are not available for product designers so there is a clear gap of knowledge in this area. In addition to this are, there is also a need for a method to assess and compare LED-based lighting products to support product designers. This research has studied the eco-design of LED-based lighting products through the description and examination of a case study (described in chapter 4). A descriptive model of the eco-design process followed was developed, and based on this model, and other insights learnt during the process, a new approach was defined to eco-design LED-based lighting products (Fig. 8.1). The approach (explained in detail in chapter 7) shows the design stages of the process, and which eco-design tools have to be used in each stage. Figure 8.1 shows (in red colour) how the findings from chapter 5 (method to assess and compare LED-based lighting products) and chapter 6 (Lifespan of LED-based lighting products: Eco-design guidelines) contributed, with the case study research (chapter 4), the development of the approach. The 'method to compare and assess LED-based lighting products' informed the SimaPro (SP) eco-design tool and, consequently, the Environmental Product Declarations (EPD) and eco-labels eco-design tools, which are informed by the SP results. The eco-design guidelines created in the 'Lifespan of LED-based lighting products' informed the Eco-design guidelines (EDG) and Eco-design Guidelines Checklists (EDG-CH) eco-design tools.

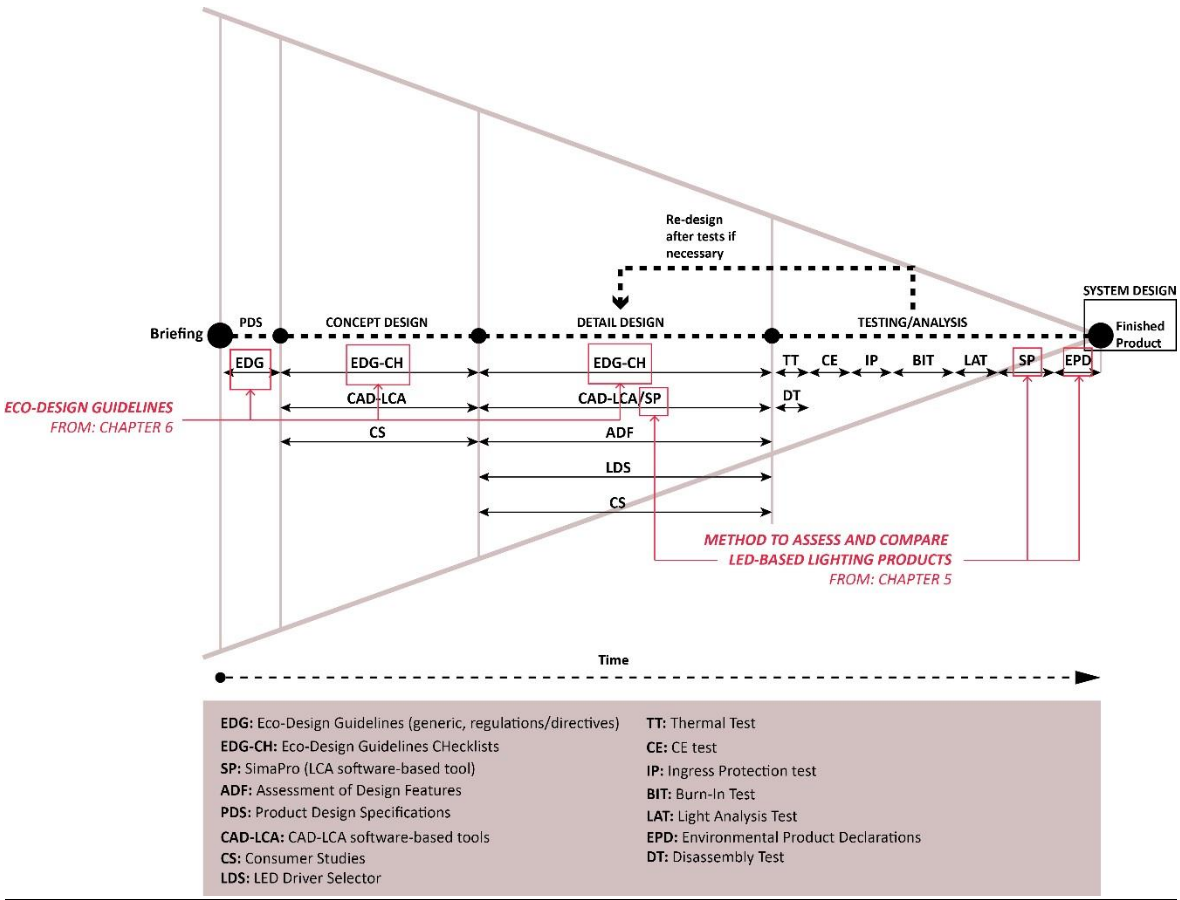


Figure 8.1. Approach to eco-design LED-based lighting products showing the integration of chapter 5 and 6 output in the approach.

The approach is divided in four stages (PDS, concept design, detail design, testing/analysis), and includes the utilisation of fourteen eco-design tools. The aim of these is to support eco-decision-making processes. In each stage different eco-design tools are utilised as follows:

In the PDS stage: Eco-design guidelines; in the concept design stage: Eco-design guidelines checklists, CAD-LCA (e.g. Solidworks-sustainability), and Consumer Studies (e.g. questionnaires, focus groups, interviews); in the detail design stage: Eco-design guidelines checklists, CAD-LCA, Simapro, assessment of design features method, LED Driver selector, consumer studies; in the testing and analysis stage: Thermal test, CE test, IP test, burn-in test, light analysis test, environmental product declarations, and disassembly test. Eco-design guidelines have to be used at the beginning of the process (PDS stage) to provide a reference to create the product design specifications, eco-design guidelines checklists have to be used to ensure the initial eco-design guidelines are accomplished. At this stage are also used CAD-LCA tools such as Solidworks-Sustainability to assess and compare concepts and design decisions (e.g. material selection), and consumer studies should also be conducted to ensure the eco-design features implemented are accepted by the end-user. At the detail design stage, eco-design guidelines checklists are used to ensure the eco-design guidelines defined in the PDS are considered in each design iteration as much as possible. In addition, CAD-LCA tools should also be used to assess and compare design solutions and different versions. Alternatively, Simapro can also be used if the prototype is defined enough and more accuracy and/or completeness in the assessment is required, although SP should only be used exceptionally at this stage. The assessment of design features method should be used at this stage to assess the design features, in each design iteration, that can be improved to reduce the environmental impact of the lighting product. LED driver selector should also be used to optimise the LED-LED driver system in order to reduce its energy consumption. Consumer studies have to be conducted, as it was done in the concept design stage, to ensure the consumer accept the eco-design features implemented. At the testing and analysis stage several tests are conducted to: 1) Extend the durability (lifespan) and safety of the lighting product (thermal test, CE test, IP test, burn-in test), 2) To facilitate its repair and disassembly (disassembly test), 3) To obtain the light performance of the lighting product (Light analysis test), and 4) To obtain and communicate to the consumer the environmental profile of the lighting product (Environmental Product Declarations: EPD, and Eco-labels). Some of these tests (CE test) also have to be conducted because they are compulsory in lighting products marketed in the EU. Although there is not a priority order of implementation of the different eco-design tools in the concept and detail design stages, during the testing and analysis stage a specific order of implementation should be followed for each type of test or analysis in order to

have data available for the subsequent test. Thermal test and disassembly tests can be conducted soon after the first prototype is available at the end of the detail design stage. Once these tests have been passed satisfactorily and the lighting product has the final design, the CE test, the IP test, the Burn in test and the light analysis test should be conducted. Finally, an environmental impact assessment should be conducted using the LCA-based method developed with Simapro (SP) to inform an EPD or eco-label. The approach also recommends to design a system around the final lighting product at the end of the process to further reduce its environmental impact. This system can comprise several strategies such as: Long warranties, old lighting products refund systems, the possibility to upgrade (aesthetically and technically) the lighting product facilitated by modular design and free or discounted upgrades, and the provision of information to the end user about how to repair, use and recycle the lighting product.
In terms of design iterations during the design process, within the concept design stage and detail design stage design iterations and feedback loops occur, although these are not described in the approach. However, between the detail design and the testing and analysis stages these iterations and feedback loops are indicated (Fig. 8.1) because they occur between different design process stages, and also to highlight that the lighting product will have to be re-designed (and return to the detail design stage again) until the lighting product do not pass all the tests satisfactorily.

8.2 - Future research

There are several topics that could be studied further in future research. These topics are related to the following areas studied in this research: the approach proposed, the eco-design tools and methods used and available, and the method used to assess and compare LED-based lighting products.

<u>Approach:</u>

Due to the limitations related with the generalisation of findings from a single case study, the descriptive process model (approach) developed should be evaluated with several case studies with different types of users and contexts (e.g. company types) to validate and improve its effectiveness and usability.

Eco-design Tools and methods:

There is a need for the development of eco-design tools and methods that can integrate CAD software-based tools with LCA, so product design decisions' environmental impact can be assessed simultaneously in real time in the CAD tool without the use of additional LCA-based software tools. Early attempts of this, much needed, research can be seen in tools such as Solidworks-Sustainability. However, the integration should be universal in any design-related software, not only in one brand of software. In addition, the current tools (i.e. Solidworks) which integrate CAD with LCA, have not been researched-developed enough to provide the same breadth and depth of functionalities (i.e. end of life scenarios, databases, LCIA methods) provided by stand-alone LCA-based software tools such as simapro. Ecodesign tools need to 'add value' and/or address gaps in existing design processes if they are to be used.

Method to compare and assess LED-based lighting products:

The LCA-based method used to assess and compare LED-based lighting products needs to be further studied because the results are based on many assumptions which, although typical in any modelling exercise, do not allow the conduct of a reliable and objective comparative assessment. Information about the useful life (lifespan) and the end of life of the lighting products is made on assumptions of how long the lighting product will last and how it will be disposed, although this is not a problem in itself, it becomes an issue when we compare two lighting products and assume that each have a different lifespan or that will be recycled instead of disposed. It is true that a well designed and tested lighting product will last more than one that has been not designed and tested properly, or that a lighting product that is easy to dismantle and recycled will have more possibilities to be recycled than other that cannot, but we need factual data (field work studies and a formula) that can allow us to factor these differences in the LCA-based method. In addition, there is a need to study how to compare LED-based lighting products with different light quality (CCT and CRI), because, to date, it is not understood with exactitude, how differences in CCT and CRI values between lighting products affect their energy consumption. Dimming is also an issue that needs to be addressed in relation with lighting products. In theory, lighting products that can be dimmed cause less environmental impact than lighting products that cannot be dimmed, because when the product is dimmed consumes less energy, and also last longer because it is not used at full capacity. However, it is difficult to take this into account in when two lighting products are assessed and compared, because it is not known how much reduction in energy should be considered (in the LCA-based method) when a lighting product utilises a dimmer compared with one that do not utilise them.

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Appendix

APPENDIX 2.1

Databases:

Hazardous Substances Data Bank (HSDB) (U.S. National Library of Medicine, 2015):

It is a database that provides toxicology data about 5,000 substances.

European Aluminium Association database (European Aluminium, 2015):

It provides European datasets for the production of primary and recycled aluminium, as well as for transformation of aluminium into semi-finished products.

European Federation of Corrugated Board Manufacturers (FEFCO) (FEFCO, 2015):

It provides a European database of life cycle studies of corrugated board and paper. This database is updated every three years.

International Iron and Steel Institute (IISI) (IISI, 2015): It provides worldwide data about life cycle inventory for steel products.

The EcoInvent database (Ecoinvent, 2015):

It is the world's leading supplier of consistent and transparent data. It provides Life Cycle Inventory (LCI) data on energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management services, and transport services.

CPM LCA Database (Swedish lifecycle centre, 2015):

It is an on-line database that provides access to over 500 datasets. All LCI datasets can be viewed in three formats: SPINE, a format compatible with the ISO/TS 14048 LCA data documentation format criteria, and ILCD. A Life Cycle Impact Assessment (LCIA) method calculator provided can calculate the impact of the datasets using three different LCIA methods: EPS, EDIP and ECO-Indicator.

EIME (Bureau Veritas CODDE, 2015):

This database provides cradle to gate life cycle Inventory (LCI) data from materials, processes, and electrical/electronic components. The databases comprise Ecoinvent database (8800 modules) and generic and sectorial databases. The generic databases consist of the European Life Cycle Database (ELCD) database with over 300 modules and the materials and processes database developed by CODDE with over 700 modules. It also comprises sectorial databases such as: E&E (over 400 modules), Textiles database (over 400 modules) and transport database (150 modules).

Esu-services databases (ESU-services, 2015):

It is a compilation of various databases consisting of: Updated Ecoinvent V2.2. database, Food products database (i.e. Animal products, vegetables production, fish, etc.), NEEDs database (which contains international industrial life cycle inventory data on future electricity supply systems, future material supply and future transport services), US-EI database and Agribalyse database (which contains LCI of agricultural products.

Eurofer data sets (Eurofer, 2015):

It provides European Average LCI data for stainless steel flat coil and quarto plate products. The datasets are based on average site-specific data (gate to gate) of European and global steel producers.

Global Emission Model for Integrated Systems (GEMIS) (IINAS, 2015):

It is a database which contains LCI datasets covering processes for energy (fossil, nuclear, renewable), materials (metals, minerals, plastics), transport (person and freight) and recycling processes.

IVAM LCA Database (IVAM UvA BV, 2015):

It is a database comprising about 1350 (cradle to grave) processes related with the following areas: Energy carriers and technologies, materials production, transport services and end-of-life treatment. It is a compilation of several databases such as: APME, Buwal, ETH 96, and additional LCA data originating from own Life Cycle Assessment (LCA) studies.

Plastics Europe Eco-profiles database (PlasticsEurope, 2015):

It provides average (cradle to gate) LCI datasets of the main polymers and their intermediates produced in Europe.

The Boustead Model (Boustead Consulting, 2015):

The Boustead Model is an extensive database with LCI datasets. It also includes software which enables the user to manipulate the data in the datasets of the database, and to select different formats to present the datasets. It is based on two parts. The first one include 33300 LCI industrial processes from almost any country, and over 6000 LCI from industrial processes involved with materials processing. The second part allows to build an additional 6000 industrial processes.

US Life Cycle Inventory (USLCI) Database (NREL, 2015):

This database provides cradle-to-gate, gate-to-gate, and cradle-to-grave LCI datasets associated with producing materials, components, or assemblies in the U.S.

APPENDIX 2.2

Standards and certifications:

Standards for LED lamps and LED modules:

- BS EN 62031:2008+A2:2015 (BSI, 2008a):

LED modules for general lighting. Safety specifications.

- BS EN 62471:2008 (BSI, 2008b):

Photobiological safety of lamps and lamp systems.

- IEC 62560:2011 (IEC, 2011):

Self-ballasted LED-lamps for general lighting services > 50 V - Safety specifications.

- BS EN 62560:2012+A1:2015 (BSI, 2015a):

Self-ballasted LED-lamps for general lighting services by voltage > 50 V. Safety specifications.

- IEC 62612:2013 (IEC, 2013):

Self-ballasted LED lamps for general lighting services > 50 V - Performance requirements.

- IEC 60061:2015 DB (IEC, 2015a):

Lamp caps and holders together with gauges for the control of interchangeability and safety.

- IEC 60838-2-2:2006+AMD1:2012 CSV (IEC, 2012):

Miscellaneous lamp holders - Part 2-2: Particular requirements - Connectors for LED-modules.

- CIE 127:2007 (CIE, 2007):

Measurement of LEDs.

- BS EN 13032-1:2012 (BSI, 2012): Light and lighting - Measurement and presentation of photometric data of lamps and luminaires - Part 1: Measurement and file format.

Standards for LED - control gear:

- BS EN 61347-1:2001+A1:2008 (BSI, 2001b):

Lamp control gear. General and safety requirements.

- BS EN 61347-2-13:2006 (BSI, 2006a):

Lamp control gear. Particular requirements for d.c. or a.c. supplied electronic control gear for LED modules.

- IEC 62384:2006+AMD1:2009 CSV. Consolidated version (IEC, 2009a):

DC or AC supplied electronic control gear for LED modules – Performance requirements.

- BS EN 62386-101:2014 (BSI, 2014a):

Digital addressable lighting interface – Part 101: General requirements - System.

- BS EN 62386-102:2014 (BSI, 2014b):

Digital addressable lighting interface. General requirements. Control gear.

- BS EN 62386-207:2009 (BSI, 2009):

Digital addressable lighting interface - Part 207: Particular requirements for control gear - LED modules (device type 6)

- BS EN 61547:2009 (BSI, 2008c):

Equipment for general lighting purposes. EMC immunity requirements.

Standards for LED luminaires:

- IEC 60598 series (IEC, 2014b):

Luminaires - Part 1: General requirements and tests.

- BS EN 60598-1:2008 (BSI, 2008d):

Luminaires. General requirements and tests.

- BS EN 60598-2-1:1989 (BSI, 1989):

Luminaires. Particular requirements. Specification for fixed general purpose luminaires.

- IEC 62717:2014 (IEC, 2014a):

LED Modules for General Lighting - Performance requirements.

- BS EN 55015:2001 (BSI, 2001a):

Limits and methods of measurement of radio disturbance characteristics of electrical lighting and similar equipment.

- BS EN 61000-3-3:2008 (BSI, 2008e):

Electromagnetic compatibility (EMC). Limits. Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current ≤ 16 A per phase and not subject to conditional connection.

- BS EN 61000-3-2:2006+A2:2009 (BSI, 2006b):

Electromagnetic compatibility (EMC). Limits for harmonic current emissions (equipment input current ≤ 16 A per phase.

- IEC 62722-1:2014 (IEC, 2014c):

Luminaire performance - Part 1: General requirements.

- IEC 62722-2-1 :2014 (IEC, 2014d) :

Luminaire performance - Part 2-1 : Particular requirements for LED luminaires

- IEC 61547:2009 (IEC, 2009b):

Equipment for general lighting purposes - EMC immunity requirements.

- BS EN 61000-3-2:2014 (BSI, 2014c):

Electromagnetic compatibility (EMC). Limits. Limits for harmonic current emissions (equipment input current ≤ 16 A per phase).

- CISPR 15:2013+AMD1:2015 CSV Consolidated version (IEC, 2015b):

Limits and methods of measurement of radio disturbance characteristics of electrical lighting and similar equipment.

- BS EN 62493:2015 (BSI, 2015b):

Assessment of lighting equipment related to human exposure to electromagnetic field.

- EU 244/2009 and EU 874/2012: Ecodesign and energy labelling – household lamps (European Community, 2009b).

- EU 1194/2012: Ecodesign requirements for directional lamps, light emitting diode lamps and related equipment (European Community, 2012).

- IES LM-79-08: Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products (IES, 2008).

- IES LM-80-08: Approved Method: Lumen Maintenance Testing of LED Light Sources (IES, 2008).

- IES TM-21-11: Projecting Long Term Lumen Maintenance of LED Light Sources (IES, 2011).

- IES LM-82-12: LED Light Engine Measurements (IES, 2011b).

Standards for LED components:

- Zhaga standards (Zhaga, 2015):

  It Is a global consortium of lighting manufacturers that aim at standardizing LED light engines and associated components. It also aims to simplify the architecture and design of LED luminaire design and manufacturing. Standardization of components means that more components can be interchanged, thus contributing to extend the lifespan of the

LED-lighting product when new components appear (upgrade) or when old components fail (maintenance).

Below are mentioned the main *certifications* that apply to LED-based lighting products:

- European Community (CE) certification-marking (European Commission, 2015b):

  This is a compulsory certification-marking for lighting products that are commercialized in EU. It ensures a minimum level of quality standards and facilitates its commercialization within EU countries.

- Ingress Protection (IP) test (IEC, 2015c):

  This is a certification that indicates the protection against solids and liquids of the lighting product. The certification indicates the level of protection with 2 numbers. For example, an IP34 certification indicates that the lighting product has a protection against solid hazards of 3 (from a 0-6 scale) and a protection against liquids of 4 (from a 0-9 scale).

APPENDIX 4.1

Questions of the focus group - consumer survey of final concept:

Questions - aesthetics:

- What is your first design impression of this product?
- What about the material used, any comments?
- What about the size of the luminaire?
- Any ideas of improvements?

Questions - application:

- Proposed application in the description was pendant, track, surface, floor, table. Please rank the applications in order usability.
- Can you think of any other appropriate applications?

Questions - performance:

- Why there is a need to develop and commercialize Ecolights?
- Is dimmability an important feature? If so why and where?
- What light temperature color (Kelvin) do you think is preferred for the Scandinavian market?
- Is there any need of having other light color (RGB)?
- What beam angle is needed?
- What kind of CRI is needed and, will it be different for different applications?
- There are different kinds of control systems for lamps. Which ones do you prefer and are needed?
- Is the brand of the diode important as a sales argument?

Questions - recycling:

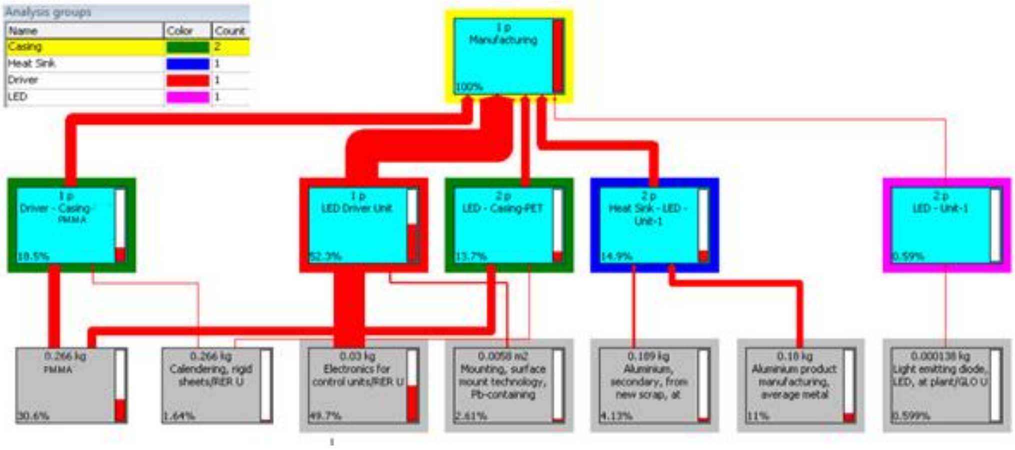
- The concept of the luminaire is that it shall be 100% recyclable. Do you think there is a demand for this kind of recyclable unit and also how important is this as sales argument?

APPENDIX 4.2

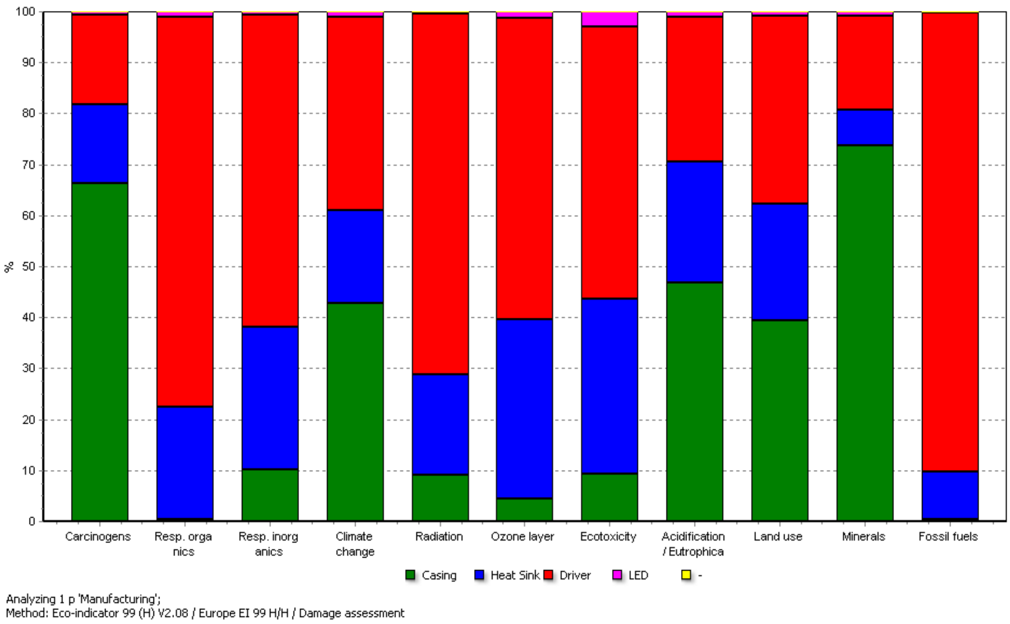
Comparative LCA of prototype I and prototype II:

LCA of Prototype I:

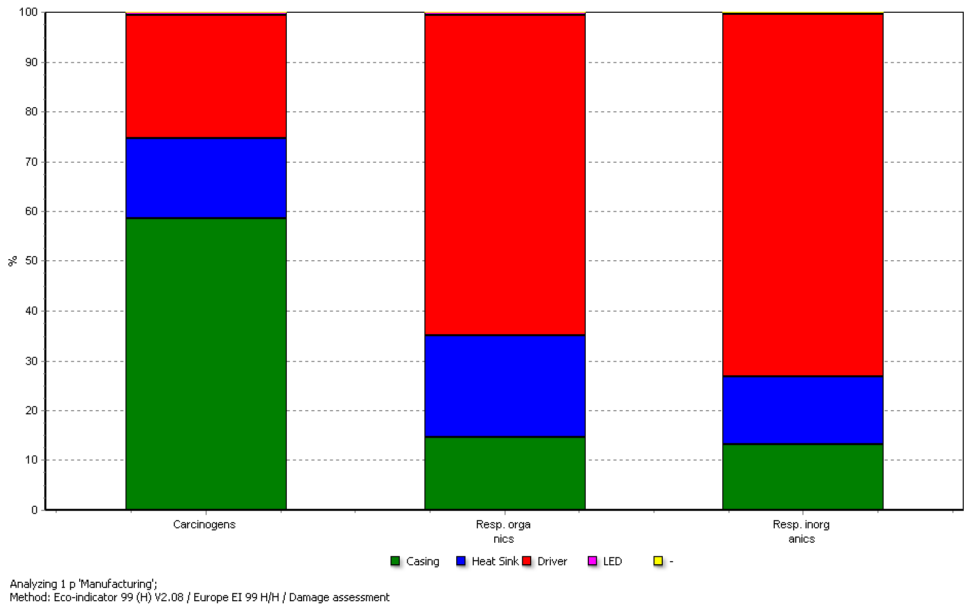
Environmental impact results of manufacturing stage:



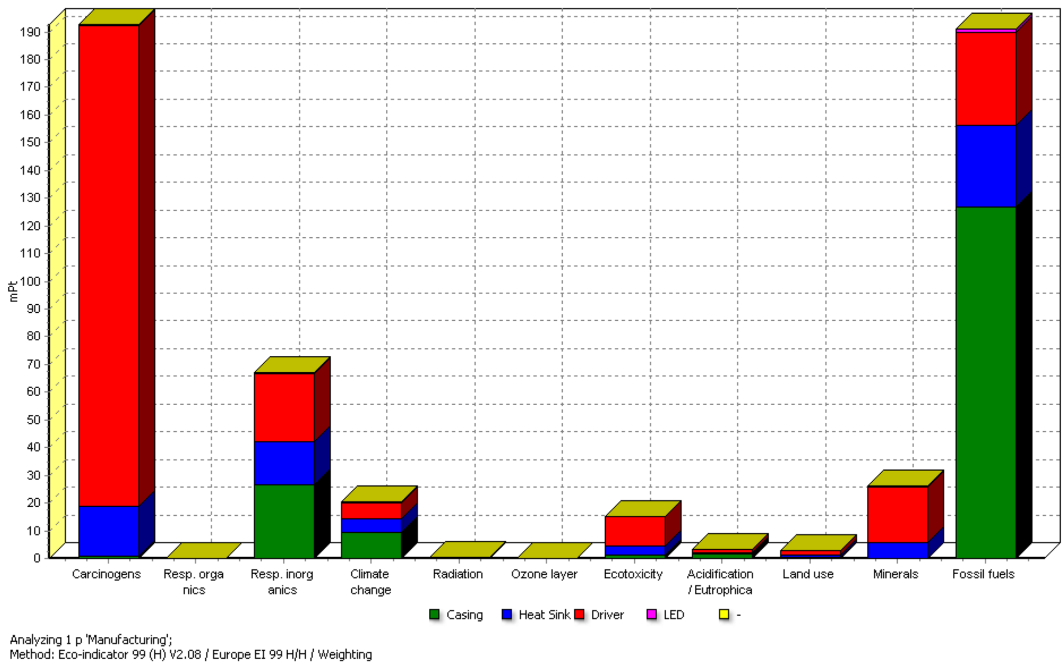
Damage assessment of components mid points:



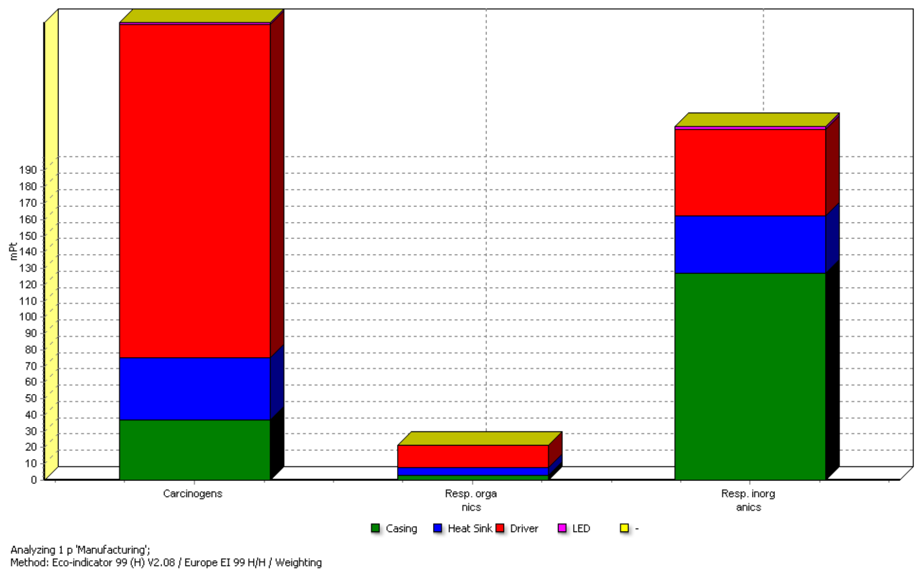
<u>Damage assessment of components end points:</u>



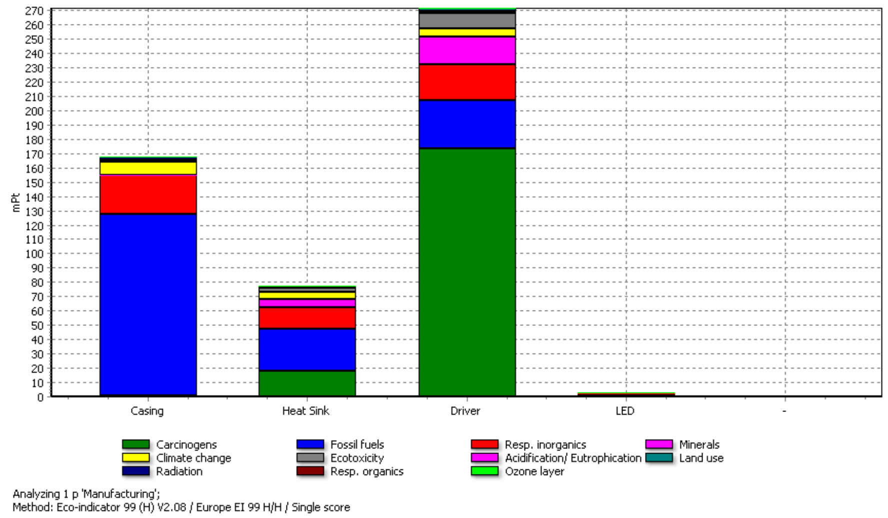
<u>Weighting of components mid points:</u>



Weighting of components end points:



Single score of components mid points:



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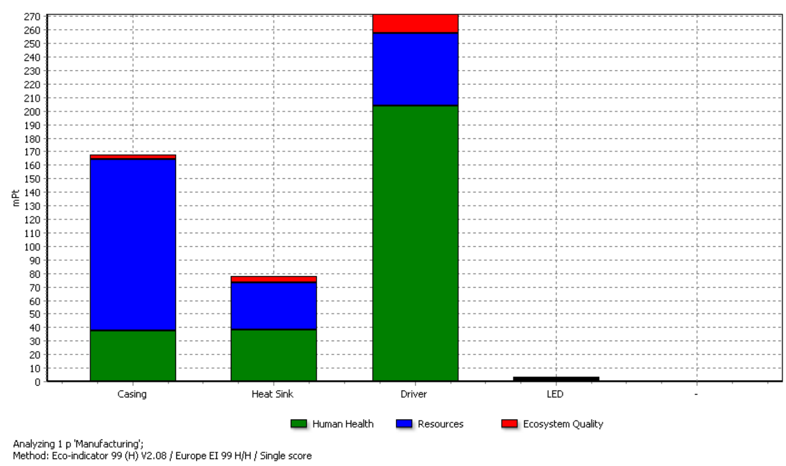
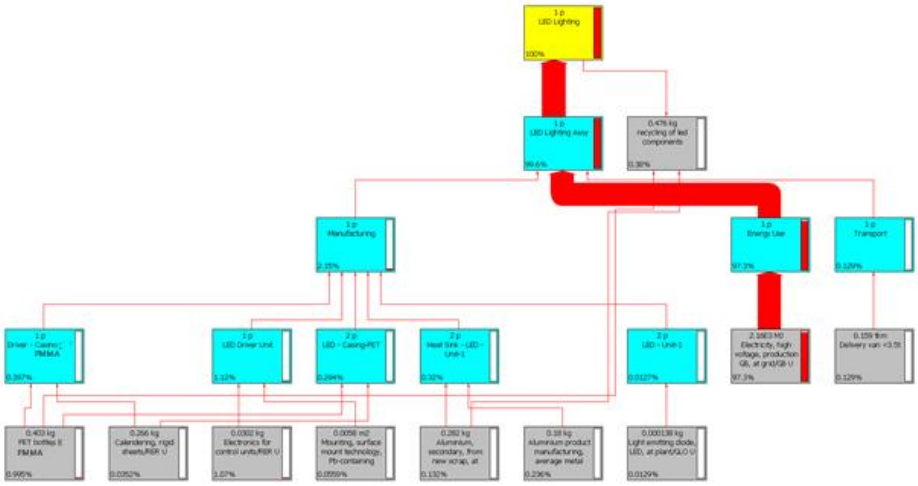
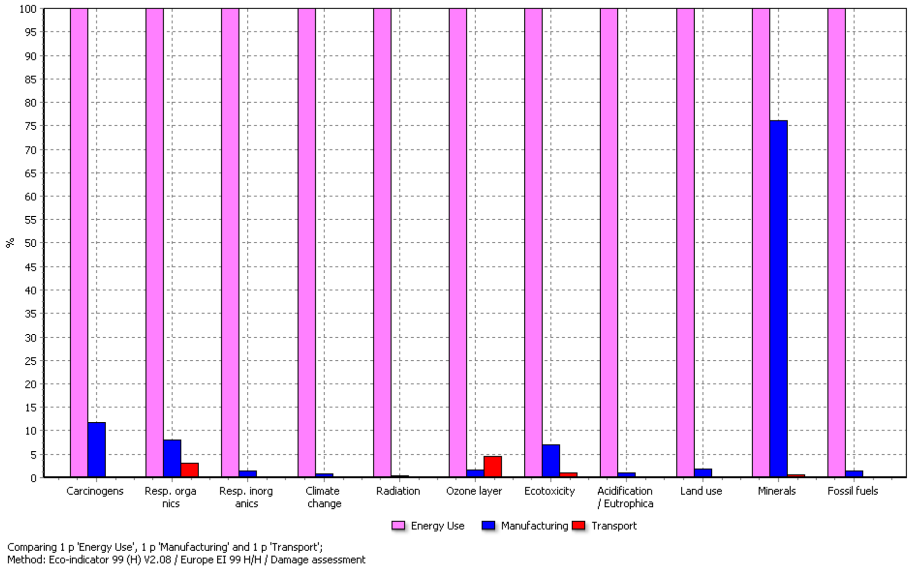


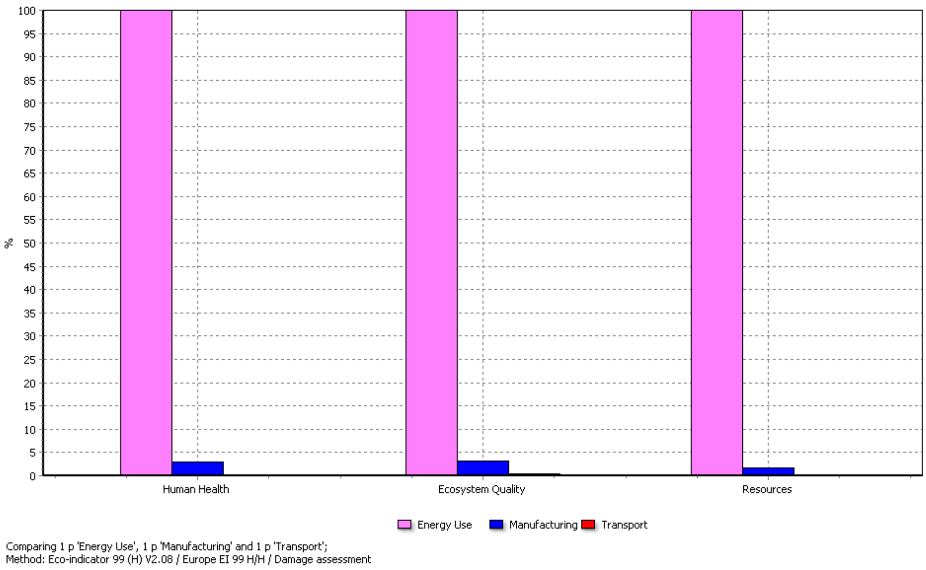
<u>Environmental impact results of product life cycle stages:</u>



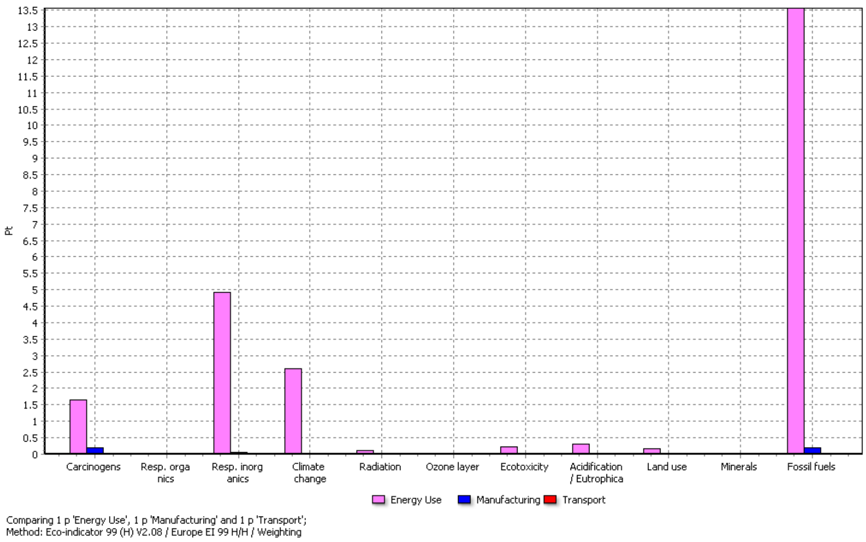
<u>Damage assessment of life cycle stages mid points:</u>



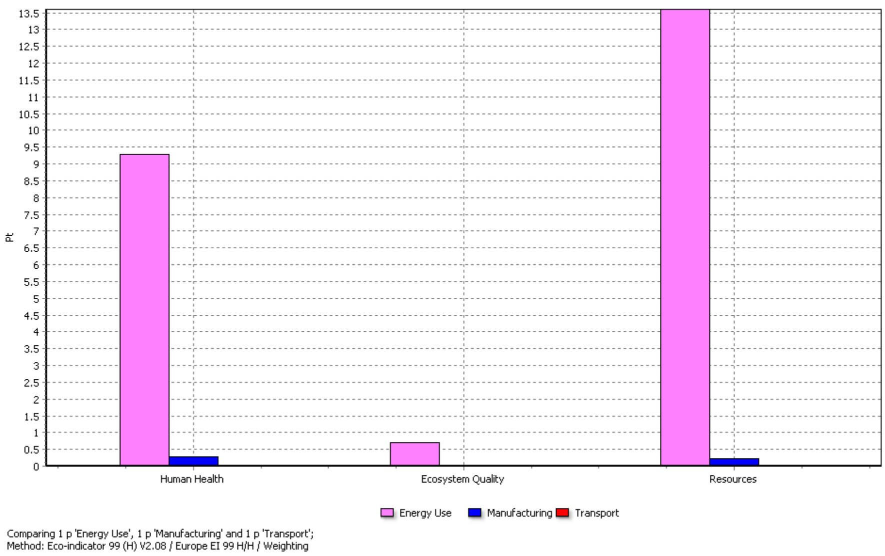
<u>Damage assessment of life cycle stages end points:</u>



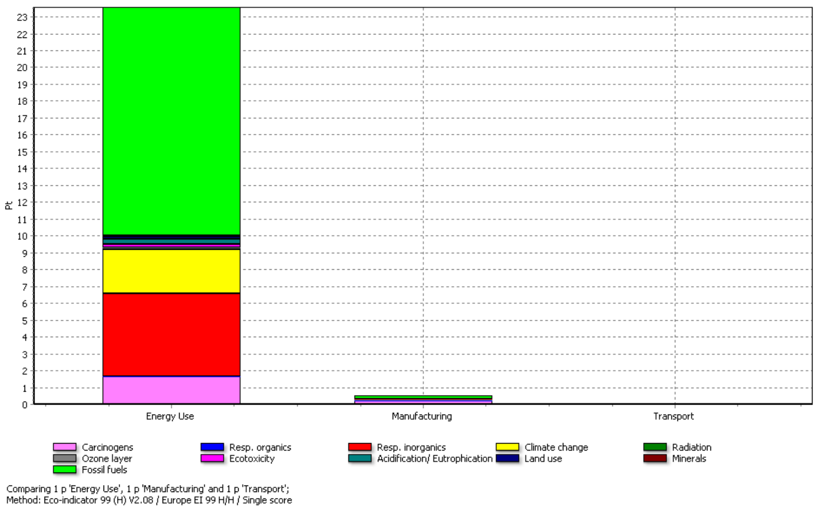
Weighting of life cycle stages mid points:



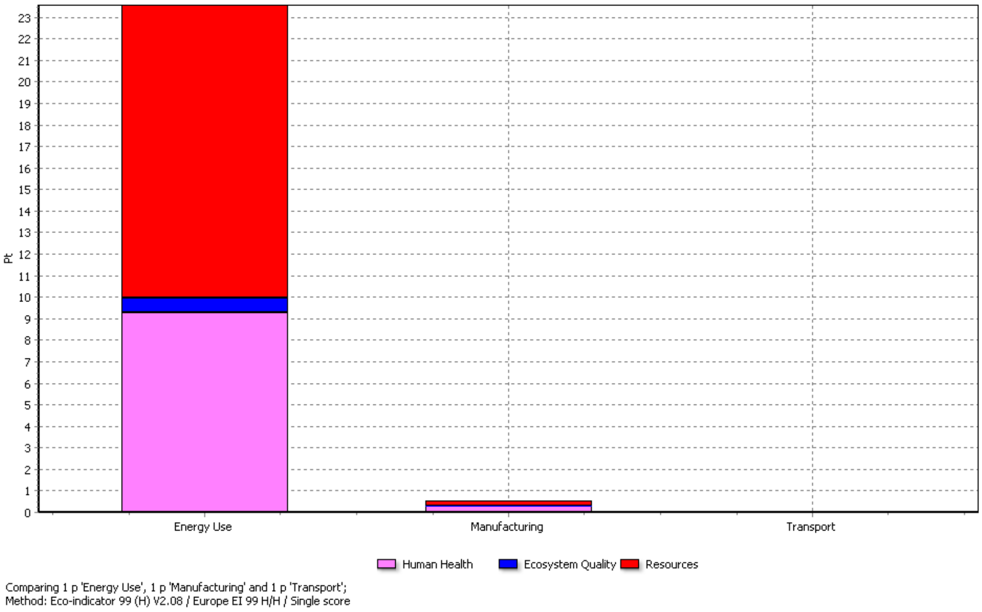
Weighting of life cycle stages end points:



Single score of life cycle stages mid points:

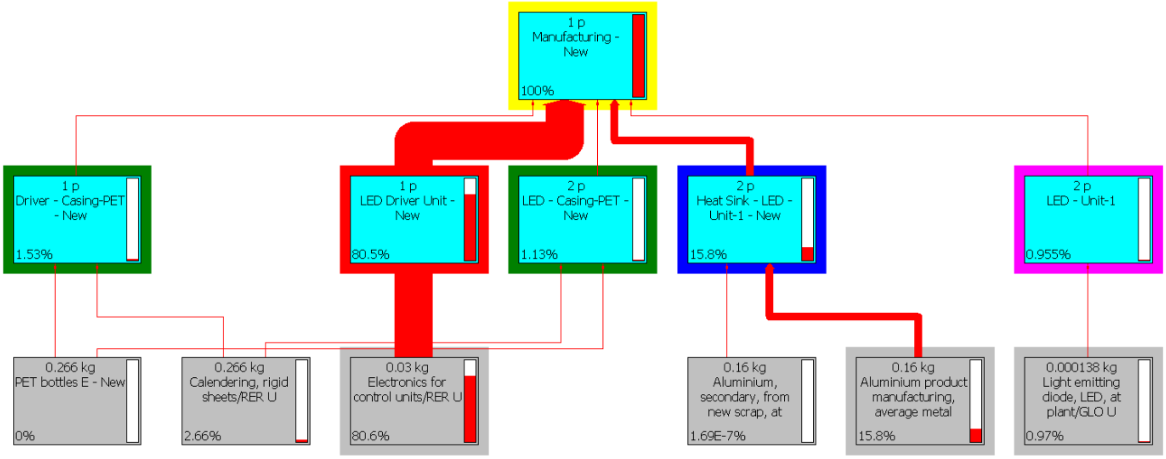


Single score of life cycle stages end points:

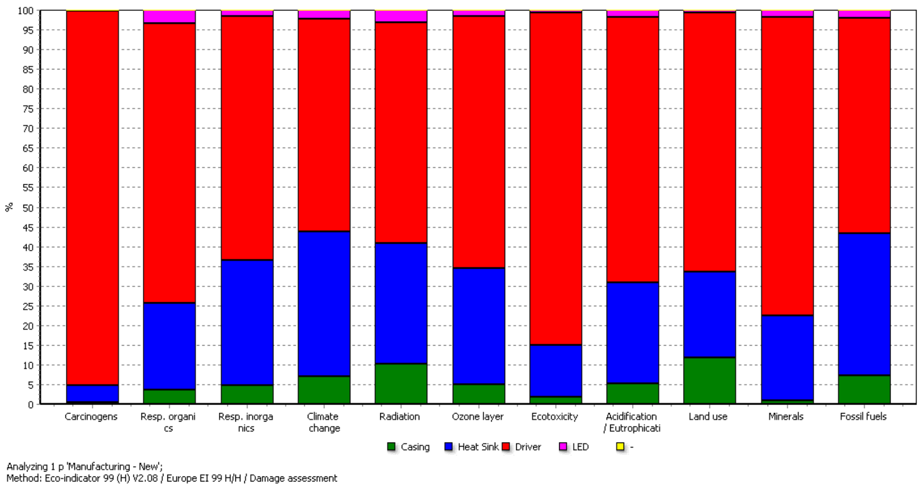


LCA of Prototype II:

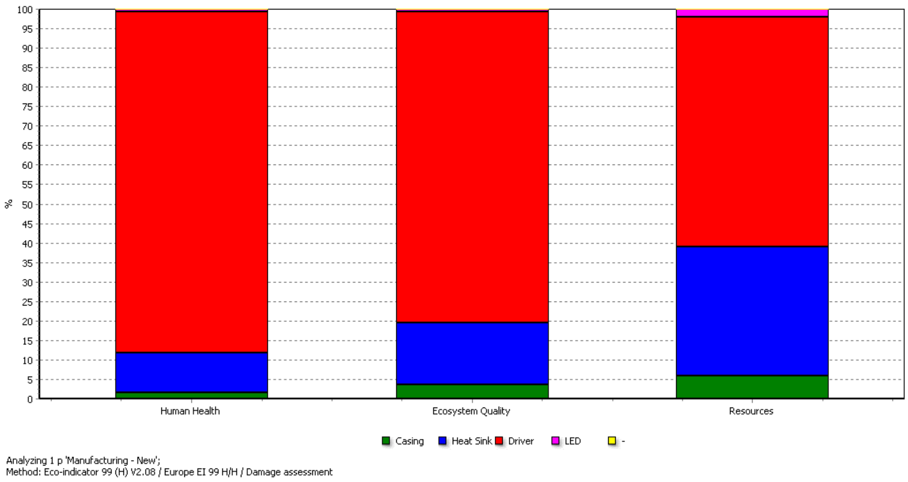
Environmental impact results of manufacturing stage:



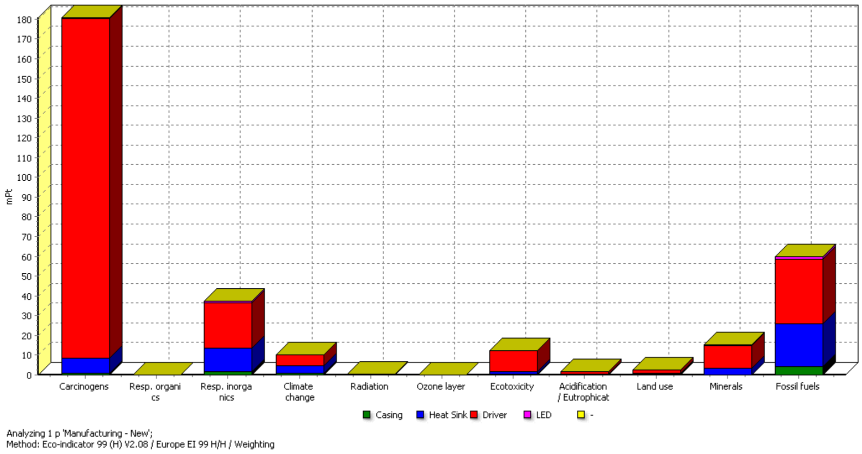
Damage assessment of components mid points:



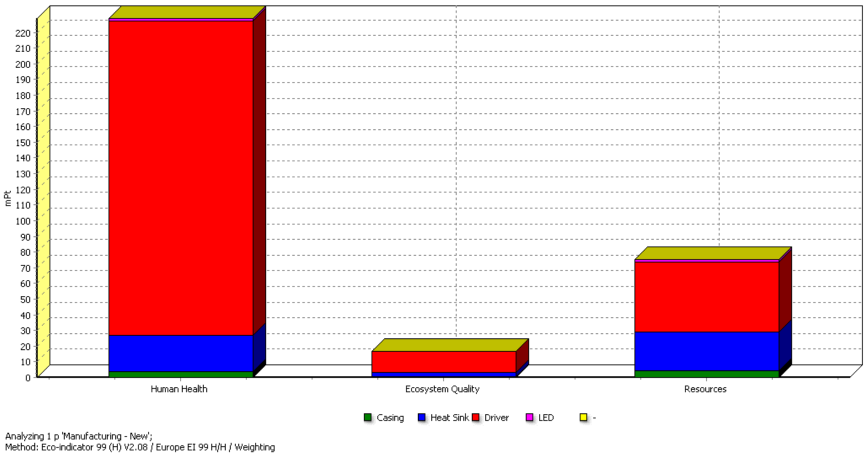
Damage assessment of components end points:



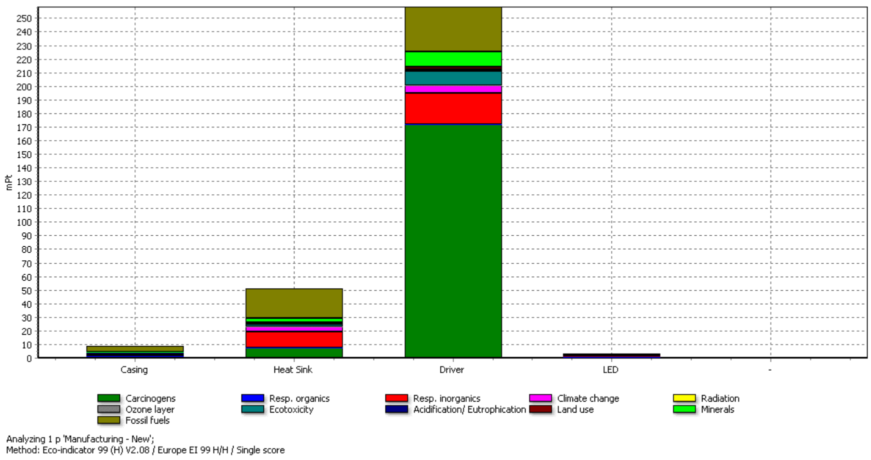
Weighting of components mid points:



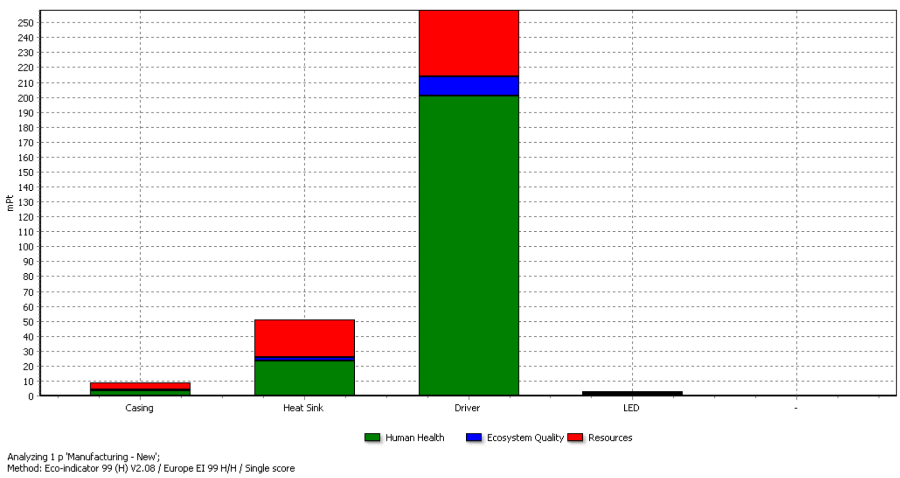
Weighting of components end points:



Single score of components mid points:

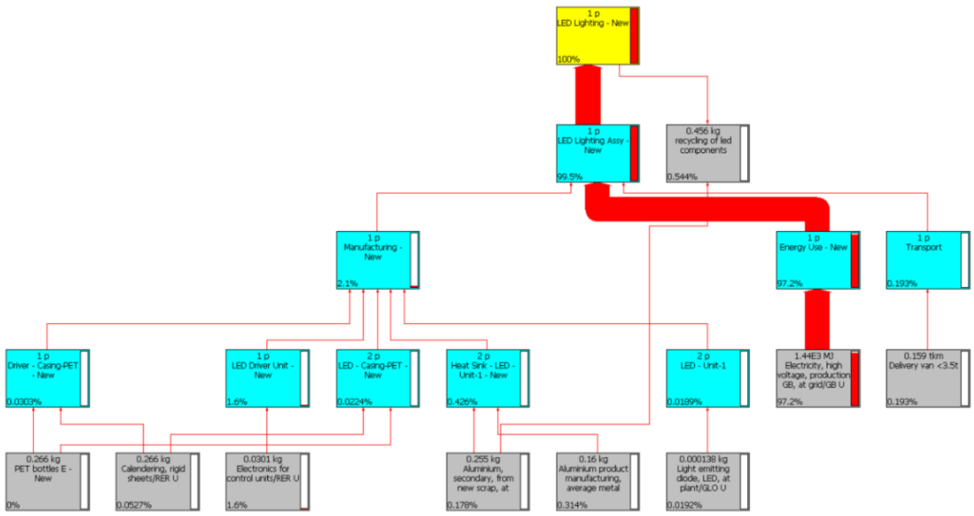


Single score of components endpoints:

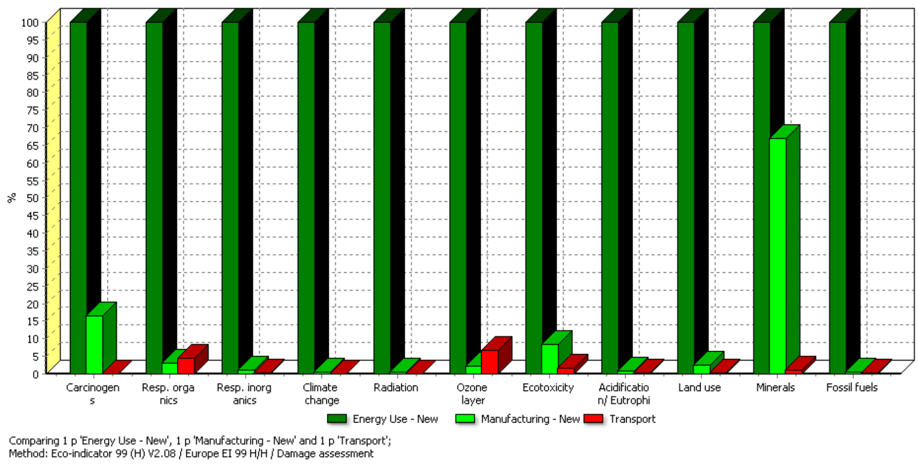


Single score of components endpoints:

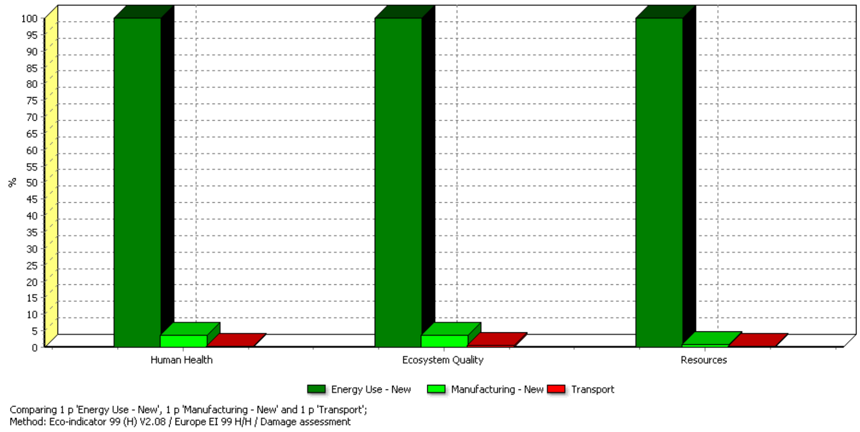
Environmental impact results of product life cycle stages:



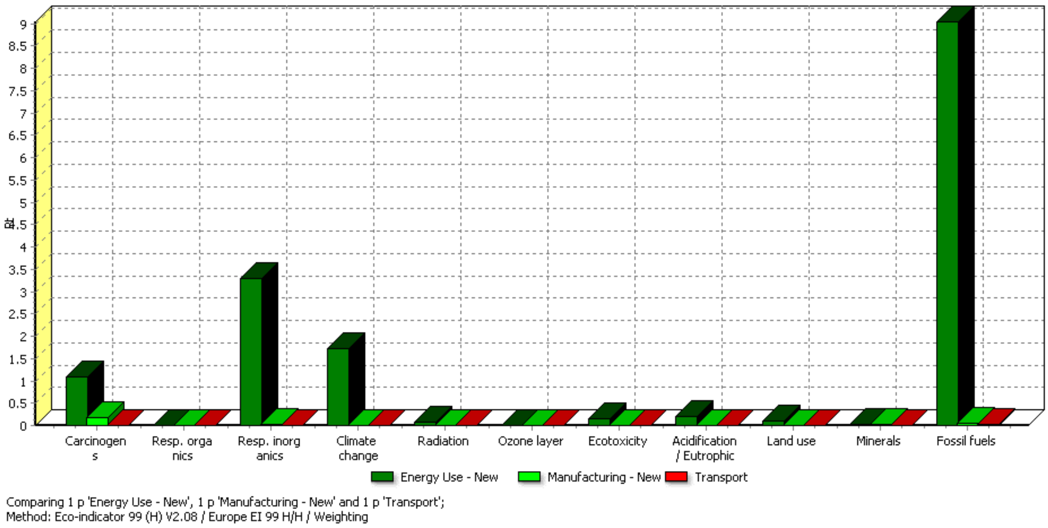
Damage assessment of life cycle stages mid points:



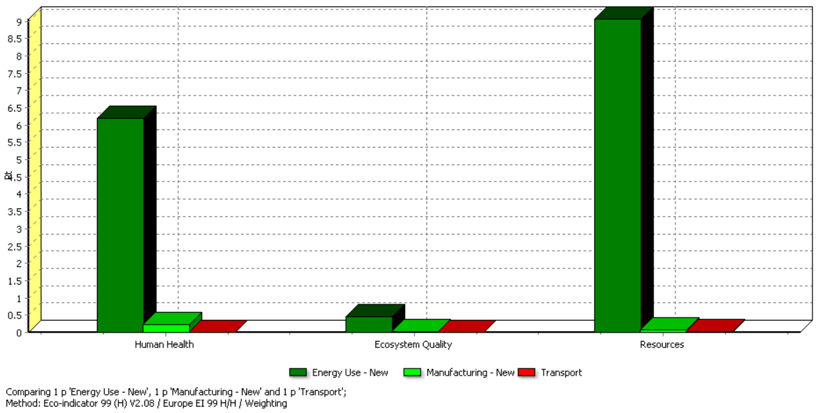
Damage assessment of life cycle stages end points:



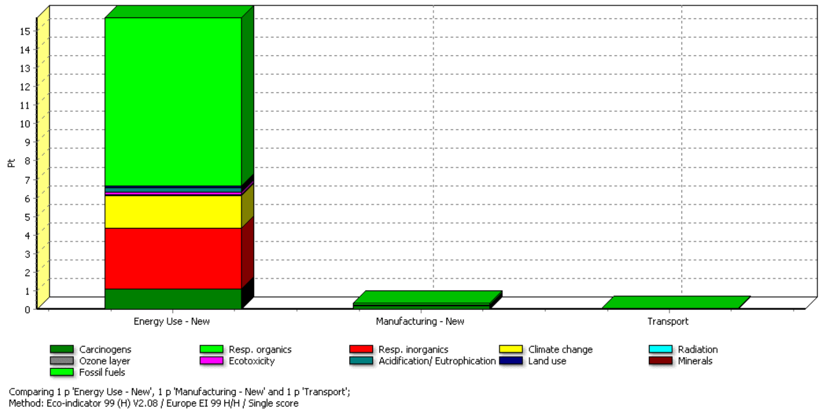
Weighting of life cycle stages mid points:



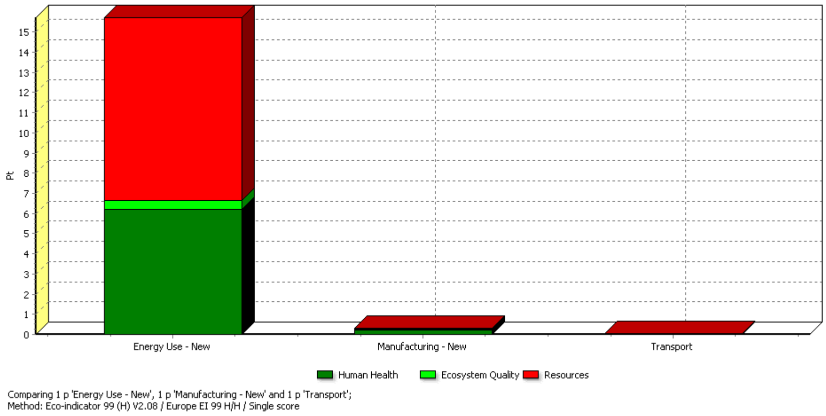
Weighting of life cycle stages end points:



Single score of life cycle stages mid points:



Single score of life cycle stages end points:



APPENDIX 4.3:

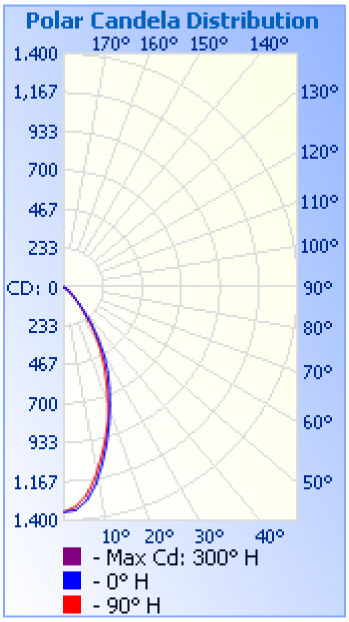
Light distribution analysis results carried out with goniometer:

Photometrics Pro

Luminaire Photometric Report

- [Evaluation Version]

Filename:	**EUL - test_3 units**
Lamp Output:	-1 lamp, rated Lumens/lamp: 948
Max Candela:	1,358.5 at Horizontal: 300Â°, Vertical: 3Â°
Input Wattage:	17.2
Luminous Opening:	Point
Test:	9910025
Test Date:	5/22/2014 3:37:07 PM
Photometry :	Type C
Nema Type:	5 X 5



Roadway Summary

Cutoff Classification:		N/A
Distribution:		Type VS
Max Cd, 90 Deg Vert:		0
Max Cd, 80 to <90 Deg:		0
	Lumens	% Lamp
Downward Street Side:	485.8	51.2%
Downward House Side:	474.8	50.1%
Downward Total:	960.5	101.3%
Upward Street Side:	0	0%
Upward House Side:	0	0%
Upward Total:	0	0%
Total Lumens:	960.5	101.3%

Flood Summary

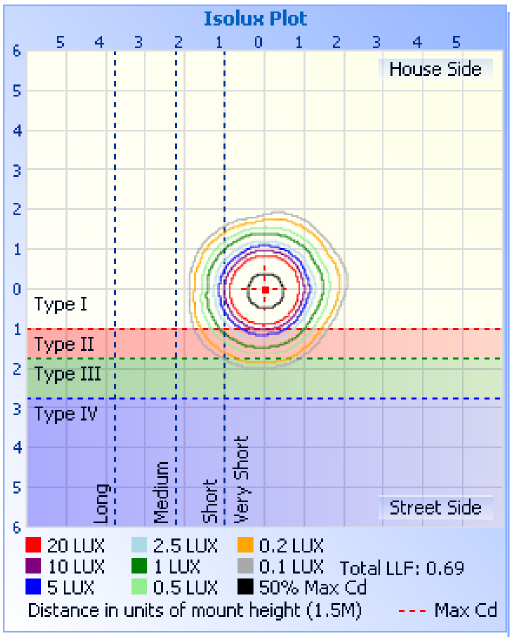
	Efficiency	Lumens	Horizontal Spread	Vertical Spread
Field (10%):	93.8%	889.1	85.2	84.4
Beam (50%):	51.2%	485.5	46.5	46.4
Total:	101.3%	960.1		

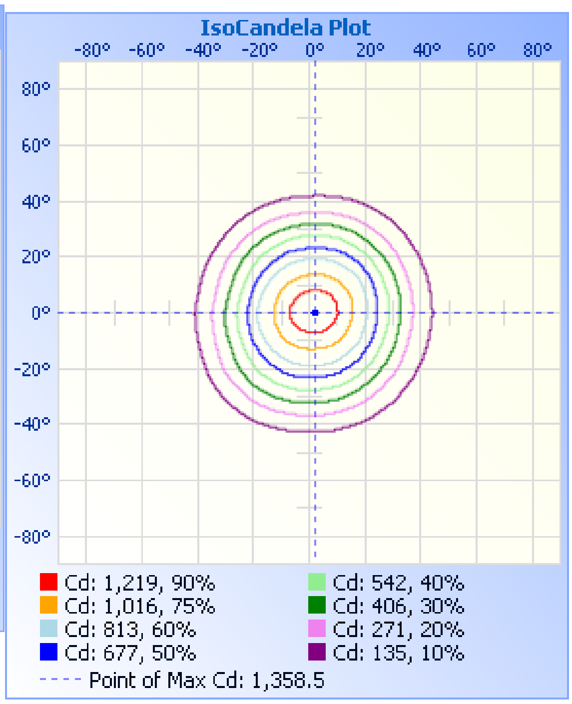
Zonal Lumen Summary

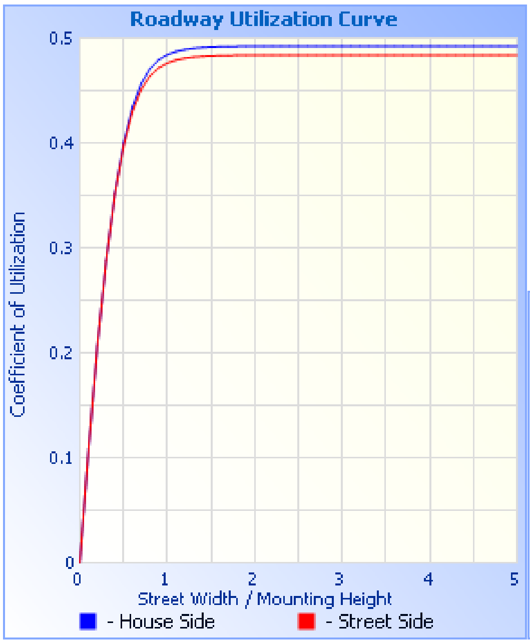
Zone	Lumens	% Lamp	% Luminaire
0-30	673.0	71%	70.1%
0-40	864.8	91.2%	90.1%
0-60	957.1	101%	99.8%
60-90	2.4	0.3%	0.2%
70-100	0.0	0%	0%
90-120	0	0%	0%
0-90	959.5	101.2%	100%
90-180	0	0%	0%
0-180	959.5	101.2%	100%

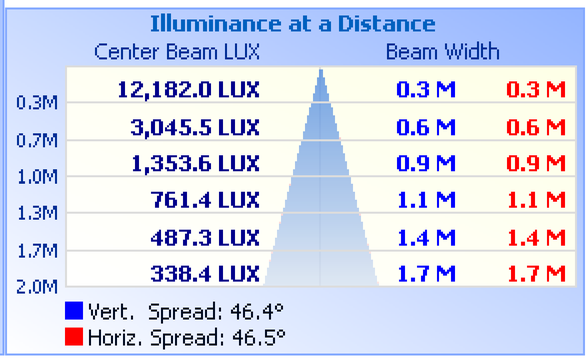
Lumens Per Zone

Zone	Lumens	% Total	Zone	Lumens	% Total
0-10	119.3	12.4%	90-100	0	0%
10-20	270.7	28.2%	100-110	0	0%
20-30	283.0	29.5%	110-120	0	0%
30-40	191.7	20.0%	120-130	0	0%
40-50	74.1	7.7%	130-140	0	0%
50-60	18.2	1.9%	140-150	0	0%
60-70	2.4	0.2%	150-160	0	0%
70-80	0.0	0.0%	160-170	0	0%
80-90	0	0.0%	170-180	0	0%


Isolux Plot
House Side
Type I
Type II
Type III
Type IV
Long
Medium
Short
Very Short
Street Side
20 LUX
10 LUX
5 LUX
2.5 LUX
1 LUX
0.5 LUX
0.2 LUX
0.1 LUX
50% Max Cd
Total LLF: 0.69
Distance in units of mount height (1.5M)
Max Cd


IsoCandela Plot
Cd: 1,219, 90%
Cd: 1,016, 75%
Cd: 813, 60%
Cd: 677, 50%
Cd: 542, 40%
Cd: 406, 30%
Cd: 271, 20%
Cd: 135, 10%
Point of Max Cd: 1,358.5


Roadway Utilization Curve
Coefficient of Utilization
Street Width / Mounting Height
- House Side
- Street Side


Illuminance at a Distance
Center Beam LUX
Beam Width
0.3M 12,182.0 LUX 0.3 M 0.3 M
0.7M 3,045.5 LUX 0.6 M 0.6 M
1.0M 1,353.6 LUX 0.9 M 0.9 M
1.3M 761.4 LUX 1.1 M 1.1 M
1.7M 487.3 LUX 1.4 M 1.4 M
2.0M 338.4 LUX 1.7 M 1.7 M
Vert. Spread: 46.4°
Horiz. Spread: 46.5°

APPENDIX 5.1

BoM of L1

Part	Component	Material	Simapro Material	Database	Weight (g)
Main-structure		Stainless steel	Stainless steel hot rolled coil	ELCD	2836
Screen-structure		Iron	Pig iron, at plant/GLO U	Ecoinvent	344
Screen		Parchment	Paper, wood-containing, LWC, ar regional storage/RER S	Ecoinvent	104
Cable (3.2 m)	Jacket	PVC	PVC Injection moulding E	Industry data 2.0	52.24
	Wire	Copper	Copper Wire, technology mix, consumption mix, at plant cross section 1mm2 EU-15S	ELCD	42.4
Plug	Housing	ABS	Acrylonitrile-butadiene-styrene copolymer, ABS, at plant/RER S	Ecoinvent	6.75
	Internal switch comp.	Copper	Copper, primary, at refinery/GLO S	Ecoinvent	2.24
Bulb holder		ABS	Acrylonitrile-butadiene-styrene copolymer, ABS, at plant/RER S	Ecoinvent	25
		Iron	Cast iron, at plant/RER S	Ecoinvent	3
Base		Iron	Pig iron, at plant/GLO S	Ecoinvent	872
Switch	Housing	ABS	Acrylonitrile-butadiene-styrene copolymer, ABS, at plant/RER S	Ecoinvent	7.35
	Metal components	Copper	Copper concentrate, at beneficiation/GLO S	Ecoinvent	0.95
LED bulb	Metal thread	Iron	Cast iron, at plant/RER S	Ecoinvent	12
	Plastic internal structure	ABS	Acrylonitrile-butadiene-styrene copolymer, ABS, at plant/RER S	Ecoinvent	18.44
	Aluminium external case	Aluminium	Aluminium alloy, AlMg3, at plant/RER S	Ecoinvent	9.965
	Heat sink plate	Aluminium	Aluminium alloy, AlMg3, at plant/RER S	Ecoinvent	13.568
	Joint-ring	ABS	Acrylonitrile-butadiene-styrene copolymer, ABS, at plant/RER S	Ecoinvent	1.2248
	Light diffuser	PET	PET (bottle grade) E	Industry data 2.0	11.18
	Printed Circuit Board (PCB)	N/A	Printed wiring board, surface mount, Pb free surface, at plant/GLO S	Ecoinvent	4.74
	LED power supply	N/A	Transformer, low voltage use, at plant/GLO U	Ecoinvent	3.0558
	Capacitor	N/A	Capacitor, electrolyte type, < 2cm height, at plant/GLO U	Ecoinvent	0.8143
	Capacitor	N/A	Capacitor, electrolyte type, < 2cm height, at plant/GLO U	Ecoinvent	0.58
	Capacitor	N/A	Capacitor, film, through-hole mounting, at plant/GLO S	Ecoinvent	0.5
	Capacitor	N/A	Capacitor, tantalum, through-hole mounting, at plant/GLO S	Ecoinvent	0.68
	Inductors	N/A	Inductor, unspecified, at plant/GLO U	Ecoinvent	0.92
	Resistor	N/A	Resistor, metal film type, through-hole mounting, at plant/GLO S	Ecoinvent	0.356

LED metal support	Aluminium	Aluminium alloy, AlMg3, at plant/RER S	Ecoinvent	13.568
Resistor	N/A	Resistor, metal film type, through-hole mounting, at plant/GLO S	Ecoinvent	0.12
Resistor	N/A	Resistor, metal film type, through-hole mounting, at plant/GLO S	Ecoinvent	0.13
Screws	Stainless Steel	Stainless steel hot rolled coil	ELCD	1.47
LED	N/A	Light emitting diode, LED, at plant/GLO S	Ecoinvent	1.4311

APPENDIX 5.2

BoM of L2

Part	Component	Material	Simapro Material	Database	Weight (g)
Housing - LED module		PET	PET - 100% recycled	N/A	240
Lid - Housing LED module		PET	PET - 100% recycled	N/A	60
Housing - driver module		PET	PET - 100% recycled	N/A	272
Lid - housing driver module		PET	PET - 100% recycled	N/A	82
Cable	Jacket	PVC	PVC Injection moulding E	Industry data 2.0	52.24
	Wire	Copper	Copper wire, technology mix, consumption mix, at plant cross section 1 mm2 EU-15S	ELCD	42.4
Plug	Housing	ABS	Acrylonitrile-butadiene-styrene copolymer, ABS, at plant/RER S	Ecoinvent	7.75
	Internal switch comp.	Copper	Copper, primary, at refinery/GLO S	Ecoinvent	2.24
Heat sink		Aluminium	Aluminium alloy, AlMg3, at plant/RER S	Ecoinvent	126
Reflector		PMMA	Polymethyl methracrylate (PMMA) beads, production mix, at plant RER	ELCD	54
Pole		Aluminium	Aluminium alloy, AlMg3, at plant/RER S	Ecoinvent	236
Base		Aluminium	Aluminium alloy, AlMg3, at plant/RER S	Ecoinvent	686
Joint-between-modules		PET	PET - 100% recycled	N/A	18
LED		N/A	Light Emitting Diode, LED at plant/GLO S	Ecoinvent	1.35
Driver	Housing	PC	Polycarbonate E	Industry data 2.0	36.16
	Printed Circuit Board (PCB)	N/A	Printed wiring board, through-hole, Pb free surface, at plant/GLO S	Ecoinvent	10.21
	Capacitor	N/A	Capacitor, electrolyte type, < 2 cm height, at plant/GLO S	Ecoinvent	10.42
	Capacitor	N/A	Capacitor, electrolyte type, < 2 cm height, at plant/GLO S	Ecoinvent	0.17
	Capacitor	N/A	Capacitor, film, through-hole mounting, at plant/GLO S	Ecoinvent	1.05
	Capacitor	N/A	Capacitor, film, through-hole mounting, at plant/GLO S	Ecoinvent	1.09
	Capacitor	N/A	Capacitor, film, through-hole mounting, at plant/GLO S	Ecoinvent	0.14
	Capacitor	N/A	Capacitor, unspecified, at plant/GLO S	Ecoinvent	1.03
	Capacitor	N/A	Capacitor, unspecified, at plant/GLO S	Ecoinvent	0.87
	Capacitor	N/A	Capacitor, unspecified, at plant/GLO S	Ecoinvent	0.14
	Capacitor	N/A	Capacitor, unspecified, at plant/GLO S	Ecoinvent	0.57
	Resistor	N/A	Resistor, metal film type, through-hole mounting, at plant/GLO S	Ecoinvent	0.4
	Inductor	N/A	Inductor, unspecified, at plant/GLO S	Ecoinvent	6.48
	Inductor	N/A	Inductor, ring core choke type, at plant/GLO S	Ecoinvent	1.46
	Inductor	N/A	Inductor, ring core choke type, at plant/GLO S	Ecoinvent	2.44
	Transformer 1	N/A	Transformer, low voltage use, al plant/GLO S	Ecoinvent	36.35
	Transformer 2	N/A	Transformer, low voltage use, al plant/GLO S	Ecoinvent	3.56

	Brackets	N/A	Aluminium alloy, AlMg3, at plant/RER S	Ecoinvent	10.5
	Cable connectors	ABS	Acrylonitrile-butadiene-styrene copolymer, ABS, at plant/RER S	Ecoinvent	3.48
	Screws	Stainless steel	Stainless steel hot rolled coil	ELCD	0.67
	Cables	PVC	PVC Injection moulding E	Industry data 2.0	0.34
		Copper	Copper wire, technology mix, consumption mix, at plant cross section 1 mm2 EU-15S	ELCD	0.24
Circuit – platform		Aluminium	Aluminium alloy, AlMg3, at plant/RER S	Ecoinvent	84
Reflector - ring		Aluminium	Aluminium alloy, AlMg3, at plant/RER S	Ecoinvent	18
Circuit	Printed Circuit Board (PCB)	N/A	Printed wiring board, through-hole, Pb free surface, at plant/GLO S	Ecoinvent	7.3
	LED power supply	N/A	Transformer, low voltage use, at plant/GLO S	Ecoinvent	8
	Cable connectors	ABS	Acrylonitrile-butadiene-styrene copolymer, ABS, at plant/RER S	Ecoinvent	3.9
	Resistor	N/A	Resistor, metal film type, through-hole mounting, at plant/GLO S	Ecoinvent	0.36
	Diode	N/A	Diode, glass, through-hole mounting, at plant/GLO S	Ecoinvent	0.5
	Integrated circuit	N/A	Integrated circuit, IC, logic type, at plant/GLO S	Ecoinvent	0.5
	Resistor	N/A	Resistor, SMD type, surface mounting, at plant/GLO S	Ecoinvent	0.4
	Screws	Stainless steel	Stainless steel hot rolled coil	ELCD	2.76

APPENDIX 5.3

List of manufacturing processes of L1

Part	Component	Manufacturing process	Simapro process	Database
Main-structure		Laser machining	Laser machining, metal, with CO2laser 2000W power/RER S	Ecoinvent
		Drilling	Drilling, conventional, steel/RER S	Ecoinvent
Shade-structure		Welding	Welding, arc, at plant/GLO U	Ecoinvent
		Coating	Powder coating, Steel/RER S	Ecoinvent
Shade		N/A	N/A	N/A
Cable	Jacket	Extrusion	Extrusion, plastic pipes/RER S	Ecoinvent
	Wire	Zinc plating	Zinc coating, pieces/RER S	Ecoinvent
Plug	Housing	Injection moulding	Injection moulding/RER U	Ecoinvent
	Metal components	Impact extrusion	Hot impact extrusion, steel, 1 stroke/RER U	Ecoinvent
Lamp holder		Injection moulding	Injection moulding/RER U	Ecoinvent
		Impact extrusion	Cold impact extrusion, steel, 2 strokes/RER S	Ecoinvent
Base		Welding	Welding, arc, steel/RER S	Ecoinvent
Switch	Housing	Injection moulding	Injection moulding/RER U	Ecoinvent
	Metal components	Impact extrusion	Cold impact extrusion, steel, 2 strokes/RER S	Ecoinvent
LED lamp	Metal thread	Impact extrusion	Cold impact extrusion, steel, 3 strokes/RER S	Ecoinvent
	Plastic internal structure	Injection moulding	Injection moulding/RER U	Ecoinvent
	Aluminium external case	Impact extrusion	Deformation stroke, cold impact extrusion, aluminium/RER S	Ecoinvent
	Heat sink plate	Impact extrusion	Cold impact extrusion, steel, 3 strokes/RER S	Ecoinvent
	Joint-ring	Injection moulding	Injection moulding/RER U	Ecoinvent
	Light diffuser	Blow moulding	Blow moulding/RER S	Ecoinvent
	Printed Circuit Board (PCB)	N/A	N/A	N/A
	LED metal support	N/A	N/A	N/A
	LED power supply	N/A	N/A	N/A
	Capacitors	N/A	N/A	N/A
	Inductors	N/A	N/A	N/A
	Resistors	N/A	N/A	N/A
	Screws	Coating	Zinc coating, pieces/RER S	Ecoinvent
		Impact extrusion	Cold impact extrusion, steel, 2 strokes/RER S	Ecoinvent
		Wire drawing	Wire drawing, steel/RER U	Ecoinvent

APPENDIX 5.4

List of manufacturing processes of L2

Part	Component	Manufacturing process	Simapro process	Database
Housing - LED module		Injection moulding	Injection moulding/RER U	Ecoinvent
Lid - Housing LED module		Injection moulding	Injection moulding/RER U	Ecoinvent
Housing - driver module		Injection moulding	Injection moulding/RER U	Ecoinvent
Lid - Housing driver module		Injection moulding	Injection moulding/RER U	Ecoinvent
Cable	Jacket	Extrusion	Extrusion, plastic pipes/RER S	Ecoinvent
	Wire	Zinc coating	Zinc coating, pieces/RER S	Ecoinvent
Plug	Housing	Injection moulding	Injection moulding/RER U	Ecoinvent
	Internal switch comp.	Impact extrusion	Hot impact extrusion, steel, 1 stroke/RER U	Ecoinvent
Heat sink		Milling	Milling, aluminium, small parts/RER S	Ecoinvent
Reflector		Injection moulding	Injection moulding/RER S	Ecoinvent
Pole		Extrusion	Deformation stroke, cold impact extrusion, aluminium/RER S	Ecoinvent
Base		Sheet rolling	Sheet rolling, aluminium/RER S	Ecoinvent
Joint-between-modules		Injection moulding	Injection moulding/RER U	Ecoinvent
LED		N/A	Light Emitting diode, LED, at plant/GLO S	Ecoinvent
Driver	Housing	Injection moulding	Injection moulding/RER U	Ecoinvent
	Printed Circuit Board (PCB)	N/A	N/A	N/A
	Capacitors	N/A	N/A	N/A
	Resistors	N/A	N/A	N/A
	Inductors	N/A	N/A	N/A
	Transformers	N/A	N/A	N/A
	Brackets	N/A	N/A	N/A
	Cable connectors	Injection moulding	Injection moulding/RER S	Ecoinvent
	Screws	Coating	Zinc coating, pieces/RER S	Ecoinvent
		Impact extrusion	Cold impact extrusion, steel, 2 strokes/RER S	Ecoinvent
		Wire drawing	Wire drawing, steel/RER U	Ecoinvent
	Cables	Extrusion	Extrusion, plastic pipes/RER S	Ecoinvent
		Zinc plating	Zinc coating, pieces/RER S	Ecoinvent
Circuit - platform		Sheet rolling	Sheet rolling, aluminium/RER S	Ecoinvent
Reflector - ring		Milling	Milling, aluminium, small parts/RER S	Ecoinvent
Circuit	Printed Circuit Board (PCB)	N/A	N/A	N/A
	LED power supply	N/A	N/A	N/A
	Cable connectors	Injection moulding	Injection moulding/RER S	Ecoinvent
	Diode	N/A	N/A	N/A
	Integrated circuit	N/A	N/A	N/A
	Screws	Coating	Zinc coating, pieces/RER S	Ecoinvent
		Impact extrusion	Cold impact extrusion, steel, 2 strokes/RER S	Ecoinvent
		Wire drawing	Wire drawing, steel/RER U	Ecoinvent

APPENDIX 5.5

List of distribution, use, and End of Life processes used in L1 and L2

Stage	Process	Simapro process	Database
Distribution	Truck - transport	Truck 40 T	LCA Food DK
	Lorry - transport	Lorry 3.5-7.5t, EURO3/RER U	Ecoinvent
End of Life	Waste disposal scenario - Netherlands	Waste scenario/NL S	Ecoinvent
	Waste disposal scenario - France	Waste scenario/FR S	Ecoinvent
Use	Electricity production	Electricity, low voltage, production NL, at grid/NL S	Ecoinvent
		Electricity, low voltage, production FR, at grid/FR S	Ecoinvent

APPENDIX 6.1

Cover letter - Questionnaires

LED LIGHTING PRODUCTS AND LIFESPAN

This questionnaire is part of a major European funded research project (EU - FP7 - ENV.2011.3.1.9-1-Eco-innovation) carried out by 13 research institutes and SMEs from Europe called:

'cycLED: Cycling resources embedded in systems containing Light Emitting Diodes'.

The project cycLED aims at optimising the flows of resources over all life-cycle phases of Light Emitting Diodes (LED) products. The results of this project will help to save resources, reduce production costs, increase competitiveness, create jobs, and increase capacity building in Europe.

The main aim of this questionnaire is to find out the real lifespan of LED lighting products used by consumers. In order to know this, we need to get information about: 1) when LED lighting products fail to function, 2) which are the causes of these failures, 3) In which environmental and operation conditions they fail, and 4) what happens with these products after they fail.

We would really appreciate if you could spend 15 minutes to fill-in this questionnaire, as your information will help us to get real data about the current situation of LED lighting products in the market.

The information obtained in this questionnaire will be kept anonymous and confidential.

Thank you very much for your participation in this study.

Yours sincerely,
cycLED consortium.

SEVENTH FRAMEWORK PROGRAMME

European Commission

cycLED

APPENDIX 6.2

Questionnaire for LED-based lighting product manufacturers

1. What types of LED lighting product was returned to you?

a) LED lighting products used in Residential applications
b) LED lighting products used in Commercial applications (i.e. Office, retailer, hotels, etc.)
c) LED lighting products used in Industrial applications (i.e. Manufacturing facilities)
d) LED lighting products used in outdoor public spaces (i.e. Street lights, parking lots, parks, etc.)

2. In what environments was the returned LED lighting product used?

a) Indoors
b) Outdoors
c) Cold room (i.e. fridge, industrial room freezer)
d) Other

3. For how long, , has the returned LED lighting product been working since it was sold by you to the customer?

a) 0-1 years
b) 1-2 years
c) 2-3 years
d) 3-4 years
e) 4-7 years
f) More than 7 years

4. Why was the LED lighting product returned?

a) Because of failure of driver
b) Because of failure of LED
c) Because of failure of cooling system (i.e. heat sink, etc.)
d) Because of failure of dimmer
e) Because of failure of control unit
f) Because light does not illuminate the objects with the desired color (i.e. objects are not reflected with the effect desired)
g) Because it was beginning to produce less light than needed (i.e. light degradation)
h) Because the customer wanted to get new lighting products with different aesthetics
i) Because of other reasons, please explain which ones

5. If it was returned because of failure, why was it not repaired by the customer?

a) Because the manufacturer warranty covered the repair
b) Because they are very difficult to repair without advanced technical skills
c) Because there are not replacement components available in the market
e) Because of other reasons, please explain which ones

6. What do you do with the LED lighting products when they are returned to you?

a) Repair them and send them back to the customers
b) Throw them to the bin and send new products to the customer
c) Keep the parts which still function for re-use in other products, and throw the rest to the bin
d) If they don't do anything mentioned above, please explain what they do

7. How many hours per day (average) were the returned LED lighting products used?

a) 0-4 hours
b) 4-8 hours
c) 8-12 hours
d) More than 12 hours
e) I don't know

8. Did the returned LED lighting product had a dimmer?

a) Yes
b) No

9. Which was the temperature (average) of the environment where the LED lighting product was usually used?

a) -30 to -15 °C
b) -15 to 0 °C
c) 0 to 15 °C
d) 15 to 30 °C
e) 30 to 40 °C
f) More than 40 °C
g) I don't know

10. Which was the humidity where the LED lighting product was usually used? For example, Indoors average humidity = 40-60%

a) 0-20 %
b) 20-40 %
c) 40-80 %
d) 80-100 %
e) I don't know

11. In which country and area of the country was the returned LED lighting product used?

12. Which was the LED power used in the returned lighting product?

a) < 5 Watt
b) 5-20 Watt
c) 21-50 Watt
d) 51-100 Watt

e) 100-200 Watt
f) More than 200 Watt

13. Which was the forward current of the driver used in the returned LED lighting product?

a) Up to 350 mA
b) Up to 500 mA
c) Up to 700 mA
d) Up to 1.000 mA
e) More than 1.000 mA

14. Which type of cooling system (if any) was used in the returned LED lighting product?

a) Heat sink with fan
b) Heat sink with fins (without fan)
c) Heat sink with Pins (without fan)
d) Heat sink with flat plate (without fan)
e) If it was used other type, please explain which one

15. Which material the cooling system is made of?

a) Aluminium
B) Copper
c) Other. Please explain which material

If you are interested in the results of the study, please insert your e-mail and you will receive a summary of the findings.

APPENDIX 6.3

Questionnaire for consumers of LED-based lighting products

1. What types of LED lighting products do you use?

a) LED lighting products used in Residential applications
b) LED lighting products used in Commercial applications (i.e. Office, retailer, hotels, etc.)
c) LED lighting products used in Industrial applications (i.e. Manufacturing facilities)
d) LED lighting products used in outdoor public spaces (i.e. Street lights, parking lots, parks, etc.)

2. In which environment do you use the LED lighting product?

a) Indoors
b) Outdoors
c) Cold room (i.e. fridge, industrial room freezer)
d) Other

3. Did the LED lighting product failed since you purchased it?

a) yes
b) No

4. If yes, when did it fail?

a) After 0-1 years
b) After 1-2 years
c) After 2-3 years
d) After 3-4 years
e) After 4-7 years
f) After more than 7 years

5. Why did the LED lighting product fail?

a) Because of failure of driver
b) Because of failure of LED
c) Because of failure of cooling system (i.e. heat sink, etc.)
d) Because of failure of dimmer
e) Because of failure of control unit
f) Because light does not illuminate the objects with the desired color (i.e. objects are not reflected with the effect desired)
g) Because it was beginning to produce less light than needed (i.e. light degradation)
h) Because the customer wanted to get new lighting products with different aesthetics
i) Because of other reasons, please explain which ones

6. What did you do, when the LED lighting product failed?

a) I sent it to the manufacturer because it was covered by the warranty
b) I sent it to the manufacturer because it is difficult to repair without advanced technical skills
c) I sent it to the manufacturer because there were no replacement components available in the market
d) I repaired it myself
e) Because of other reasons, please explain which ones

7. How many hours per day (average) was the LED lighting product used?

a) 0-4 hours
b) 4-8 hours
c) 8-12 hours
d) More than 12 hours

8. Was the LED lighting product dimed (use of dimmer) during use?

a) Yes
b) No

9. Which was the average temperature where the LED lighting product was used?

a) -30 to -15 °C
b) -15 to 0 °C
c) 0 to 15 °C
d) 15 to 30 °C
e) 30 to 40 °C
f) More than 40 °C

10. Which was the humidity where the LED lighting product was usually used? For example, Indoors average humidity is 40-60%

a) 0-20 %
b) 20-40 %
c) 40-80 %
d) 80-100 %

11. In which country, and area of the country, was the LED lighting product used?

12. Which was the LED power used in the LED lighting product?

a) < 5 Watt
b) 5-20 Watt
c) 21-50 Watt
d) 51-100 Watt
e) 100-200 Watt
f) More than 200 Watt

13. Which was the forward current of the driver used in the LED lighting product?

a) Up to 350 mA
b) Up to 500 mA
c) Up to 700 mA
d) Up to 1.000 mA
e) More than 1.000 mA

14. Which type of cooling system (if any) was used in the LED lighting product?

a) Heat sink with fan
b) Heat sink with fins (without fan)
c) Heat sink with Pins (without fan)
d) Heat sink with flat plate (without fan)
e) If it was used other type, please explain which one

15. Which material the cooling system is made of?

a) Aluminium
B) Copper
c) Other. Please explain which material

16. Where do you dispose the LED lighting products when you don't want them anymore?

a) Domestic bin
b) Special Domestic bin for electronic scrap
c) Recycling centre
d) Manufacturer collection centre
e) Landfill
f) Other

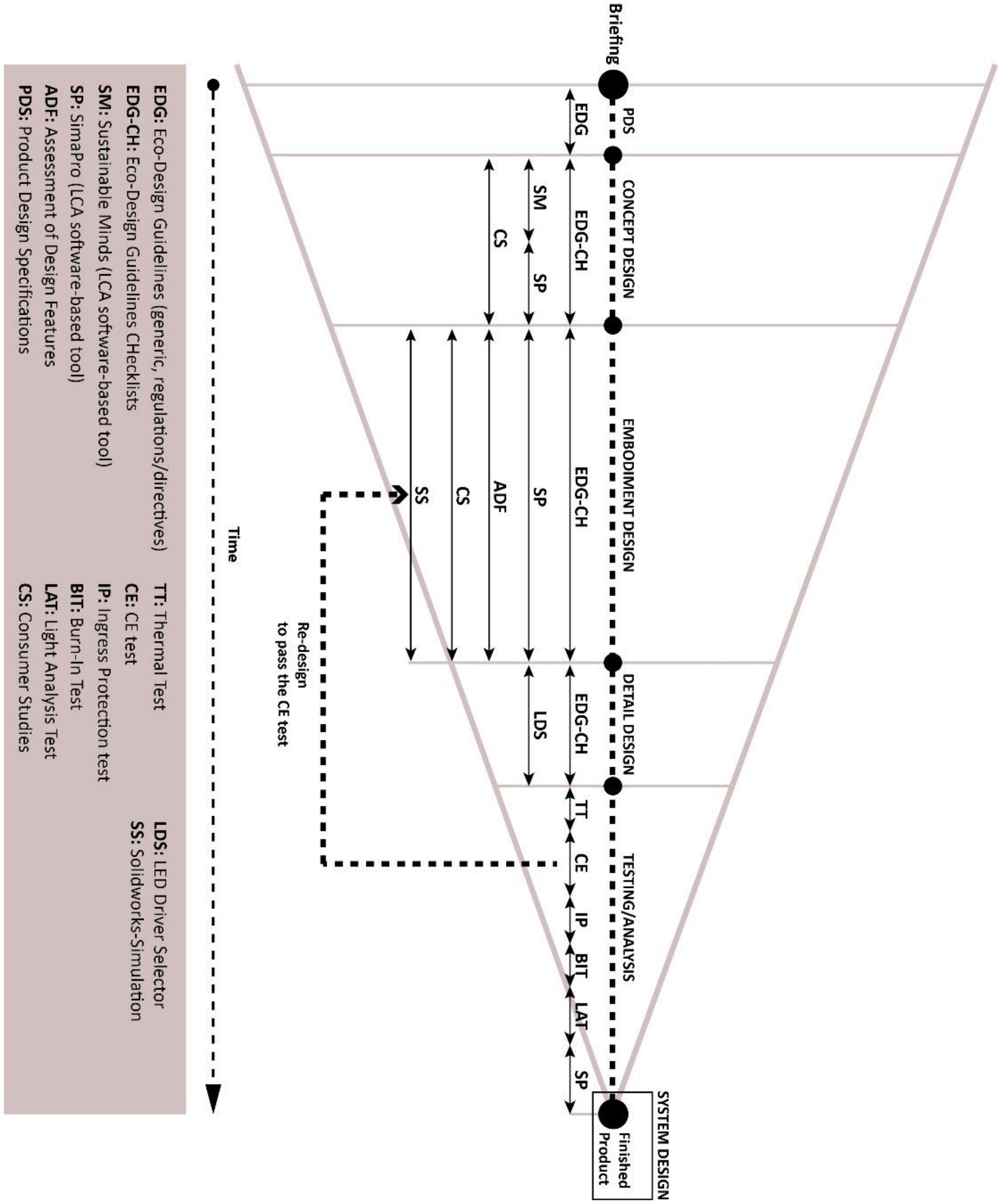
17. How long the last LED lighting product you had lasted since it was purchased until it was disposed?

a) 0-2 years
b) 2-4 years
c) 4-6 years
d) 6-8 years
e) 8-10 years
f) More than 10 years

If you are interested in the results of the study, please insert your e-mail and you will receive a summary of the findings.

APPENDIX 7.1

Descriptive model of eco-design process of case study



APPENDIX 7.2

Approach to eco-design LED-based lighting products