Integrated Approach for Sustainable Lighting Product Development

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A thesis submitted in partial fulfilment of the requirements of Nottingham Trent University for the degree of Doctor of Philosophy

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August 2019

Copyright Statement

Publication list

Su, D., Casamayor, J. and Xu, X., 2015. Utilisation of a toolbox for computer aided development of LED lighting products. *International Journal of Mechanical and Production Engineering (IJMPE)*, *3*(4), pp.56-61.

Daizhong Su, Xuemin Xu and Jose Casamayor, 2019, ‘An integrated approach for sustainable production of LED lighting products’, 8th l International Workshop on Advances in Cleaner Production, 13-15 November, 2019. Sanya, China.

Daizhong Su, Jose Casamayor and Xuemin Xu, 2015, Section 2 – Integration of Eco-production methods and tools into the development of LED lighting products, in Deliverable D.3.1: Proposal for increasing resource efficiency and reducing environmental impact from the production of LED lighting products, EU FP7 cycLED project.

Daizhong Su, Arivazhagan Anbalagan, Xuemin Xu and Zhongming Ren, 2015, Deliverable 3.2 LED Toolbox: Toolbox aiming to increase resource efficiency of LED products, EU FP7 cycLED project

Abstract

The research presented in this thesis aims to contribute to the body of knowledge and state of the art in the area of eco-lighting products by: 1) development of an integrated approach for sustainable lighting product by integrating various tools and methods through the product development process, including product design specification, conceptual design, detail design, prototyping and test, and manufacture. 2) Development of a web-based toolbox to support product designers to develop (design, test, manufacture) lighting products with low environmental impact. 3) utilisation of the integrated approach and the toolbox, a novel eco-lighting product is developed.

This study has been conducted in a real industrial context with lighting product manufacturer and other organizations involved with the lighting product life cycle, and the following main methods and techniques have been applied to collect and analyse the data, and to develop the product. A dedicated environmental and social LCA on the domestic lighting product has been conducted by using a professional LCA software. The LCI datasets are provided by its manufacturer, a Spain based company, and also fulfilled by applying ecoinvent database. The analytical results of these studies present an in-depth modelling and analysis on the table lamp product lifecycle with the aid of real manufacturing data.

This research contributes to the state of the art of eco-lighting products with the development of a novel eco-lighting product, and provide a new integrative approach to design, test, manufacture and commercialize eco-lighting products, in order to contribute to the body of knowledge in the area of approaches/methods to develop and commercialize eco-lighting products.

This research is financially supported by the cycLED project (Grant Agreement No. 282793) under the European Commission FP7 Eco-Innovation programme.

Acknowledgement

I am grateful to my Director of Study, Professor Daizhong Su for his supervision, advice and guidance from the starting of my study, and also for giving me opportunities to work on such exciting and demanding research and teaching projects. I thank my second supervisor Dr Jose Luis Casamayor for his expert advices in this study journey.

I acknowledge the financial support from the cycLED project (Grant No. 282793) under the programme of FP7-ENV-2011-ECO-INNOVATION-TwoStage.

I would like to thank the support received from Ona Product SL(Spain). They provided valuable advice in the design and quality manufacture of the products. They also kindly provided technique information needed for the research.

Finally, I would like to thank my parents, family and friends, for their unconditional love and support.

Table of Content

Copyright Statement .... ***ii***

Publication list .... ***iii***

Abstract .... ***iv***

Acknowledgement .... ***v***

Table of Content .... ***vi***

List of Figures .... ***x***

List of Tables .... ***xii***

Nomenclature .... ***xiii***

Chapter 1: Introduction ***15***

1.1 Research background **15**

1.2 Research aim and objectives **15**

1.3 Structure of the thesis **18**

Chapter 2: Literature Review ***20***

2.1 Eco-design methods **20**

2.2 Eco-design tools **21**

2.2.1 Directives and regulations 22

2.2.2 Environmental impact assessment tools 24

2.3 Life Cycle Assessment **25**

2.3.1 LCA studies related to LED lighting products 26

2.3.2 Social Life Cycle Assessment (SLCA) 29

2.4 Characteristic of LED lighting products **37**

2.4.1 Working mechanisms of LED 37

2.4.2 LED lamp life 38

2.4.3 Electrical characteristics and quality control 39

2.4.4 Luminous efficacy 39

2.4.5 Light distribution 40
2.4.6 Dimming 41

2.5 Conclusions of the literature review 42

Chapter 3: Research Methodology 45

3.1 Introduction 45

3.2 Research design and outcomes 45

3.3 Quality analysis for source data used in case studies 47

3.4 Summary 48

Chapter 4: A Web-based Toolbox to Support Eco-innovation in LED Lighting Products 49

4.1 Introduction 49

4.1.1 Demand for the toolbox of led lighting products 49
4.1.2 Web technology related to tool integration and technology base online learning 50
4.1.3 Design and manufacture of LED lighting products 52

4.2 Structure and contents: recommendations for a flexible and easy to use toolbox 53

4.3 Web development of the toolbox 54

4.3.1 Design: the toolbox structure 54
4.3.2 Contents and functionalities 55
4.3.3 Testing the Toolbox website in different browsers 67

4.4 Concluding remark 69

Chapter 5: The Integrated Approach 70

5.1 Overview of the integrated approach 70

5.1.1 The methods and tools considered in the integrated approach 70
5.1.2 The product development process considered in the integrated approach 71

5.2 Prototyping and testing 72

5.3 Hardware-based measurement tools utilized 74

5.4 Concluding remarks 75

Chapter 6: Sustainable Lighting Product Design 76

6.1 Configuration of Product Design Specifications (PDS) 76

6.2 Conceptual design 77

6.3 Detail design **79**

6.4 Lighting products utilized for demonstration of the integrated approach **82**

6.5 Conclusions **85**

Chapter 7: Experimental Investigation of the LED Lighting Product ***86***

7.1 Evaluating the optical qualities of the lighting product **86**

7.1.1 Optics criteria 86

7.1.2 Overview of selected tools 86

7.1.3 Experimental setup and implementation 87

7.1.4 Optic experiment analysis 90

Chapter 8: Environmental Life Cycle Assessment of the LED Lighting Product ***96***

8.1 Introduction **96**

8.2 Goal and scope **96**

8.2.1 Function and Functional Unit 96

8.2.2 Product General Description 97

8.2.3 System boundaries 97

8.3 Life cycle impact assessment method **98**

8.4 Calculation tool **100**

8.5 Life cycle inventory data **100**

8.5.1 Key Data for Materials and Processes 100

8.5.2 Data assumptions 102

8.6 Life cycle impact assessment results **102**

8.6.1 Default scenario analysis 102

8.6.2 Sensitivity Analysis 106

8.7 Comparison of LCA analysis results **108**

8.8 Conclusions **111**

Chapter 9: Social Life Cycle Assessment for the LED Lighting Product ***112***

9.1 Introduction **112**

9.2 Methodology for the social life cycle assessment **112**

9.3 Social life cycle impact assessment **116**

9.3.1 Social categories/subcategories and indicators definition 116

9.3.2 System description ... 124
9.3.3 Life Cycle Inventory and quality data ... 125
9.3.4 Social Life Cycle Impact Assessment ... 132
9.3.5 Results and discussion ... 140

Chapter 10: Conclusions ... 150

10.1 Discussion ... 150

10.1.1 Limitations of the research ... 150
10.1.2 Research contributions ... 151

10.2 Conclusions ... 152

10.3 Further work ... 154

Appendix ... 156

Reference ... 159

List of Figures

Figure 1-1 Structure of this thesis....................19
Figure 2-1 Stakeholder groups of SLCA....................31
Figure 2-2 Generic assessment system of SLCA impact assessment....................33
Figure 2-3 Two types of SLCA methods (Wu 2014) 34
Figure 2-4 US DOE forecast of LED efficacy improvements, relative to current conventional lighting technologies and monochromatic red LEDs and green OLEDs (US DOE, 2014)....................40
Figure 2-5 Typical light distribution from a white LED (source: Philips Lumileds) 41
Figure 4-1 Structure of the Toolbox....................54
Figure 4-2 Screen shot of the Front page of the Toolbox Website 68
Figure 4-3 Screen shot of the Software Tools page of the Toolbox Website 68
Figure 5-1 The integrated approach 70
Figure 6-1 Initial architecture of the product 80
Figure 6-2 The designed LED table lamp....................82
Figure 6-3 Driver components of the redesigned table lamp 83
Figure 6-4 Base of the redesigned table lamp 83
Figure 6-5 LED Table lamp B 84
Figure 7-1 Test room model....................88
Figure 7-2 Luminance meter used for determining reflectance of surfaces 88
Figure 7-3 Comparison of measured and simulated illuminance data for 4 lighting simulation packages, for data series A 91
Figure 7-4 Comparison of measured and simulated illuminance data for 4 lighting simulation packages, for data series E....................91
Figure 7-5 Comparison of measured and simulated illuminance data for 4 lighting simulation packages....................92
Figure 7-6 Comparison of measured and simulated in terms of overall average, maximum data value and minimum data value 93
Figure 7-7 Polar radiation pattern for the designed lighting product 94
Figure 7-8 Photometric specification of light output profile in ECOTECT 94

Figure 8-1 A schematic system for the luminaire life cycles 98
Figure 8-2 Life cycle impact results for the functional unit with the default scenario 103
Figure 8-3 Environmental impact (endpoint) per impact category of the luminaire the default scenario 104
Figure 8-4 Contribution analysis of the functional unit’s processes under default scenario105
Figure 8-5 Relative impacts (total) among scenarios 107
Figure 8-6 Results per damage category 109
Figure 8-7 Results per impact category 110
Figure 9-1 Principal phases of an LCA study 113
Figure 9-2 Relationship between stakeholders (UNEP/SETAC/LCI, 2009)............................114
Figure 9-3 Overall methodology proposed for S-LCA implementation 115
Figure 9-4 ONA’s simplified process flowchart..125
Figure 9-5 ONA’s table lamp input/output flowchart. 126
Figure 9-6 Contribution of the stages in ONA´s domestic LED table lamp SLCA results 143
Figure 9-7 The table lamp (ONA) SLCA vs PSILCA reference sector 147

List of Tables

Table 2-1 Subcategories of stakeholders........31

Table 2-2 Lifetime data of LEDs (US DOE, 2009)........39

Table 4-1 Regulations Applicable to the Current Scenario........56

Table 4-2 List of Directives Applicable To the Current Scenario........57

Table 4-3 Voluntary & National Legislation........58

Table 4-4 Indicative relevance of Legislation to production phase........59

Table 4-5 Application Tools (Software)........65

Table 4-6 Application Tools Hardware........66

Table 6-1 Technical specifications of designed LED table lamp........83

Table 6-2 BoM of benchmark product........83

Table 6-3 BoM of the redesigned LED table lamp........84

Table 7-1 Lighting software settings used for simulations........90

Table 8-1 The technical specification of the table lamp........97

Table 8-2 ReCiPe endpoint indicators description (Goedkoop et al., 2009)........99

Table 8-3 Key parameters for the materials........101

Table 8-4 Key parameters of the processes........101

Table 8-5 Life cycle impact results of product stages under default scenario........104

Table 8-6 Sensitivity results, Impact analysis total results for scenarios........107

Table 8-7 Results per damage category........109

Table 8-8 Results per impact category........110

Table 9-1 List of social subcategories in PSILCA and social indicators........117

Table 9-2 Criteria for impact category and social indicator selection........121

Table 9-3 Domestic lighting product materiality matrix........123

Table 9-4 Technical specifications of the luminaire........124

Table 9-5 Life cycle inventory of ONA domestic lighting product........127

Table 9-6 ONA’s social indicator specific data. Source: ONA and Spanish statistics........130

Table 9-7 ONA’s risk level assessment matrix........134

Table 9-8 PSILCA risk level weights. (PSILCA Social Life Cycle Impact Analysis method v1.00) 140
Table 9-9 ONA´s LED domestic table lamp SLCA absolute results per impact indicator 141
Table 9-10 Comparative results of the table lamp SLCA vs PSILCA reference sector 145

Nomenclature

AoP	Area of Protection
SLCA	Social life cycle assessment
SROI	Social Return on Investment
SIA	Social Impact Assessment
SEIA	Socio-Economic Impact Assessment
JRC	Joint Research Centre
CEMS	Certification in environmental management systems
WEEE	Waste Electrical and Electronic Equipment
PCB	Printed Circuit Board
PBB	PolyBrominated Biphenyls
PBDE	PolyBrominated Diphenyl Ether
RoHS	Restriction of Hazardous Substances
ErP	Energy-related Products
EoL	End of Life
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
AoP	Area of Protection
QALY	Quality Adjusted Life Years
SHDB	Social Hotspot Database
ASSIST	Alliance for Solid State Illumination System and Technologies
PWM	Pulse Width Modulation
VLE	virtual learning environment
PDS	Product Design Specification
EPD	Environmental Product Declarations

CCT	Correlated Colour Temperature
SROI	Social Return on Investment
SEIA	Socio-Economic Impact Assessment

Chapter 1: Introduction

1.1 Research background

This research was initiated from the cycLED project supported by the European Commission FP7 Eco-Innovation programme (cycLED, n.d.). The project consortium consists of thirteen teams from seven EU countries, with project budget €5,426,163.00 (cycLED, n.d.). As a key partner of cycLED project consortium, the Advanced Design and Manufacturing Engineering Centre (ADMEC) of Nottingham Trent University led the work package 'Production and manufacture of LEDs' and contributed to other work packages with the centre's extensive expertise in sustainable design, lifecycle assessment and eco-lighting. With the support from the ADMEC, this PhD project developed an integrated approach for sustainable lighting product development as part of the cycLED project.

With the outcome of the cycLED project, this PhD project further developed the integrated approach by including the social lifecycle assessment (SLCA) method and applied the approach into the development of a novel LED lighting product. The lighting product was manufactured by Ona Product S. L. (Ona, n.d.), a lighting product manufacturer in Spain. The product is now available in the market as a demonstrator of sustainable lighting product of the company.

1.2 Research aim and objectives

The aim of this research is to develop (design, test, prototype) and a novel eco-lighting product, and to develop an integrated eco-design approach which contributes to the understanding of how to design, manufacture and lighting products with low environmental impact. This research focuses and discusses mainly the environmental aspects of the processes involved in the approach. Although the research study the whole process, from development to market deployment, attention has been paid to the design phase where higher environmental gains can be obtained, and where product designers can have more influences.

The objectives of the research are:

- To review current eco-design methods and tools.
- To review recent studies related to LED lighting products.
- To develop an integrated approach for the development of sustainable products by integrating various tools and methods through the product development process including product design specification, conceptual design, detail design, prototyping and test, and manufacture.
- To use the proposed approach in the development of a novel sustainable LED lighting product.
- To conduct a comprehensive LCA analysis to identify the root of the negative environmental performance through the LED lighting product
- To develop a toolbox to support the integrated eco-design approach
- To implement comparative study of optical tests in goniophotometer and integrated sphere perspective.
- To conduct a detailed social LCA for the LED lighting manufacturing company

To conduct a comprehensive LCA analysis and develop improvement strategies for eco-manufacturing stage, the following sub-tasks are designed:

- To build life cycle inventory data for the components that are provided by the manufacturer. Some micro components (e.g. cable, PCB board) are required to investigate to reflect the full life cycle of the designed lamp.
- To define the different life cycle scenarios for the designed lamp, as a comprehensive LCA requires to consider three scenarios: cradle-to-grave; cradle-togate; cradle-to-cradle. As the analysis of each scenario will highlight the negative components/materials in the specific stage, which will be helpful for stakeholders to develop the targeted optimal solutions.
- To conduct the complete LCA on other commercial lamps in the market, to benchmark the values of the environmental performance for these lamps with similar materials or manufacturing steps.

To implement comparative study of optical tests in goniophotometer and integrated sphere perspective, the following sub-tasks are designed:

- The goniophotometer and tests for the designed lamp are conducted and reported in this thesis. The benchmarking values for the existing competitive LED products in the market are needed to investigate, to ensure the lighting quality of the designed lamp is acceptable by the market.
- Another key issue involved in these optical relates tests regards the harm to consumers' eyes that is usually caused by colour temperature of the luminaire. The results indicator (i.e. lumens, colour rendering index) of integrated sphere test can show the relevant qualities, which will be helpful in the iterated design stages.

To optimise the integrated approach, the following sub-tasks are designed:

- Through the complete design, prototyping and evaluating stages, the effectiveness of the integrated approach may need further improve, for instance, weather the suggested tool can perform the best functions in the allocated product development process.
- To further improve the energy quality of the designed lighting product, a few solutions will be proposed, including: adding the individual switch on/off on each lighting module; developing light control further by considering the incorporation of sensors (smart lighting) as standard, because they reduce the use of energy in all types of lighting applications, although energy savings are higher when applied lighting products that it will be used in public lighting applications.
- The integrated eco-design approach will be described and formalized in a step-by-step process model in next stage. This model will focus in the design stage, in particular, where decisions have the greatest effect in the final environmental impact of the lighting product, and where all the major decisions about the life cycle of the lighting product are carried out.
- Another sub-task should be carried out in the areas of eco-design tools used in product design processes. In particular, the seamless integration of LCA functionalities into product development process. Within this area, further understanding about the relationship between LCA results and design decisions (components, geometry, finish, etc.) will benefit to make the LCA results more meaningful for product developers.

1.3 Structure of the thesis

This thesis is structured with three distinct sections: research background and overview; theoretical and practical research development; and research conclusions as shown in Figure 1-1. The first section, Research Background and Overview, provides an introduction to the research, exploring the context of the sustainable product design, sustainability performance assessment, and the LED lighting sector. Two chapters are included in this section: Chapter 1 introduces the research context, research objectives and aims, describes the overview of this thesis structure, Chapter 2 is a review chapter, which reviews the relevant background of the designed research objectives and aim: eco-design methods and tools, and examples of these tools and methods in the LED lighting studies; studies related to environmental LCA and LED lighting products; social life cycle assessment framework, methods, and recent studies.

The second section, Theoretical and Practical Research Development, consists of seven chapters. As well as the development of a general research methodology, a series of framework and methods the proposed solution are proposed, which are based on the findings of the literature reviews. A web-based toolbox is developed for demonstrating the application of the proposed integrated eco-design approaches. The validity of the proposed approaches is then conducted by applying it in a real domestic LED table lamp. Chapter 3 offers the description of the research methodology in this research. Chapter 4 reports the development of a web-based toolbox for the sustainable product development. Chapter 5 introduces the proposed integrated eco-design method, along with a case study demonstrating the application, effectiveness and benefits of this approach are reported in Chapter 6. Chapter 7 introduces the experimental analysis for the lighting characteristics , and Chapter 8 presents the a detailed environmental LCA for the designed LED table lamp. The used datasets, explanations of calculation methods, and calculation results interpretations are reported. Chapter 9 introduces a comprehensive social life cycle assessment for the LED lighting company in the Spain.

Chapter 10 is the final chapter of this thesis, which includes the research conclusions, discussions and limitations considering the research contributions in theoretical and practical level, and recommendations for future work.

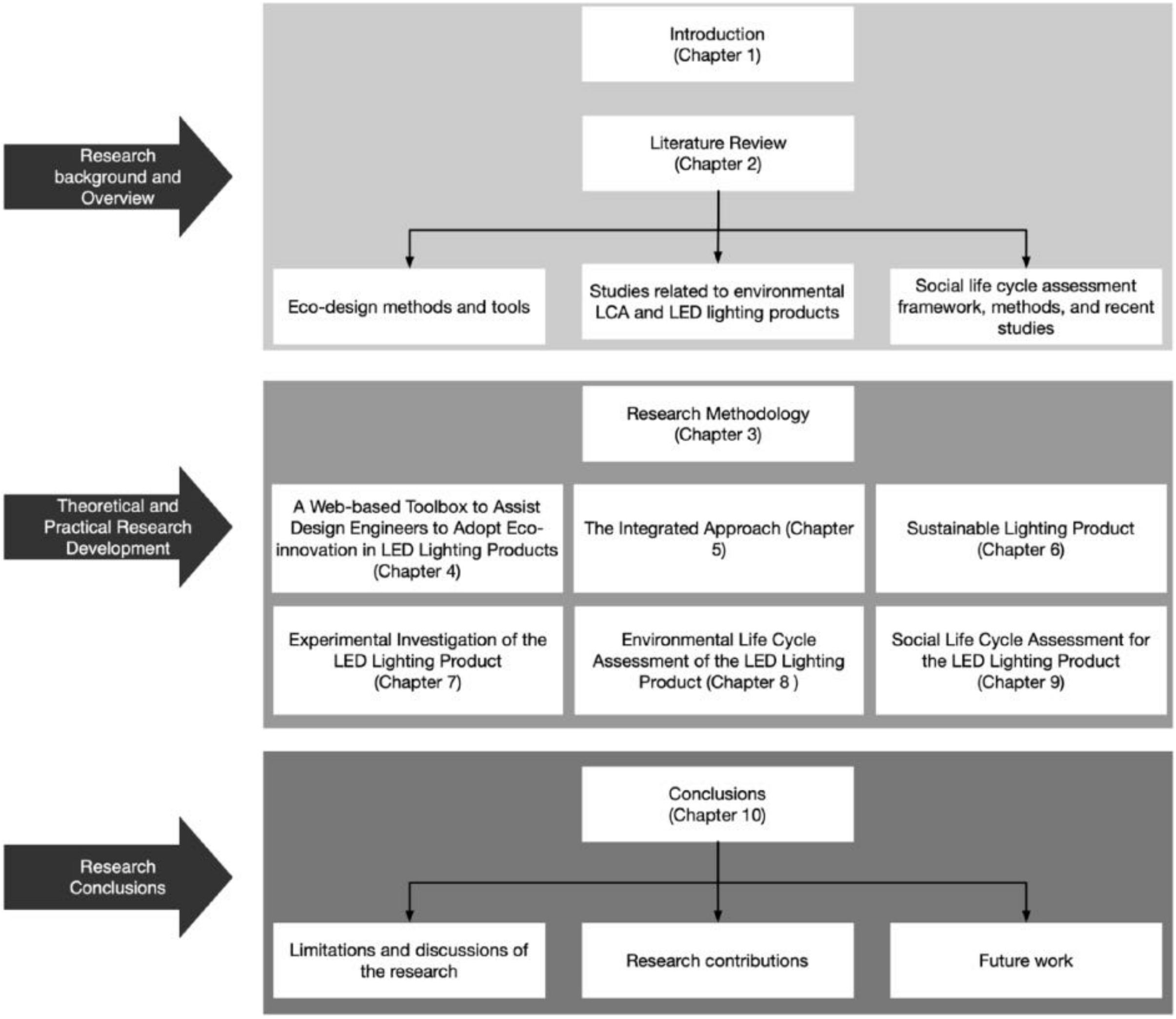

Figure 1-1 Structure of this thesis

Chapter 2: Literature Review

2.1 Eco-design methods

This section will introduce the recent studies linking the LCA and sustainable production activities including the design, manufacturing, recycling. etc. Keller et al. introduced an integrated life cycle sustainability assessment (ILCSA) methodology that combines the outcomes of the LCA, life cycle costing, and social life cycle assessment. This study used the ILCSA to examine the biorefineries production scenarios and demonstrated an ex-ante decision support for the sustainability assessment (Keller et al. 2015). Lanfang et al. developed a LCA based modelling approach, and Material Energy Flow Analysis (MEFA) was integrated to identify the recoverable and unrecoverable resources in the more complex product systems. The study examined the methodology with tracking the lifecycle iron and energy use of producing construction steels (Lanfang et al. 2015). Ribeiro et al. integrated the LCA, product design and supply chain framework to build an approach evaluating the emerging sustainable manufacturing technologies, and this approach performs environmental and economical level evaluation with the life cycle engineering foundation. The study demonstrates the feasibility with evaluating innovative manufacturing technologies (e.g. three-dimensional contoured thermoplastic sandwich structures) in the bicycle rocker design process (Ribeiro et al. 2015). Shin et al. used LCA to acquire quantitative results and integrate them into the process planning algorithm for assessing green performance of machine operations, and a Green Productivity Index was developed to represent overall environmental and productivity performance for the manufacturing phase (Shin et al. 2015). Bernier et al. developed an optimal methodology that minimizes costs to achieve zero life cycle impacts through integrating the LCA into a single or multi-objective process design optimization scenarios. The study used Ecocosts 2007 impact assessment method to evaluate compensation costs for reducing carbon dioxide emissions of a natural gas combined cycle power plant (Bernier et al. 2013). Scheepens et al. used the EVR and Circular Transition Framework to develop a new approach guiding the design of sustainable business models, and the eco-costs was applied to analyse the environmental impacts of business activities on a system level. The feasibility and utility of the approach was demonstrated by a case study describing the recreation of a sustainable water tourist system in Netherlands (Scheepens et al. 2015). Romli et al. developed an integrated eco-designmaking (IEDM) methodology, and the LCA results were incorporated in the Eco-Process model and conceptual Eco-QFD (quality function deployment) framework, in order to offer quantitative and quality evidences to support sustainable product design (Romli et al. 2014). Mestre & Vogtlander developed a design intervention method to increase the customer perceived value, which used the eco-cost to examine the eco-burden and relative values among multiple design solutions for cork products (Mestre & Vogtlander 2013). Casamayor & Su used the eco-indicator 99 that is a LCA methodology to examine the environmental performance of the main components of lighting products and their production processes. The analytical results were used in benchmarking for each optimal design iterations (Casamayor & Su 2013). Morales-Mora et al. examined the carbon emissions and wastewater flow of manufacturing acrylonitrile products in Mexico, and the LCA results were used to support that the new design of the production process has a major emission reduction than the old design (Morales-Mora et al. 2012). The reviewed studies prove that as a technological progression, the LCA enables to lead main production activities into a sustainability level. This inspired the core idea of this research that the actors in the same supply chain can contribute in building LCA or LCA based evaluations in terms of providing required data and designing evaluation indicators, and the evaluation results are shared and distilled into actions reducing the environmental burden.

2.2 Eco-design tools

The main difference between eco-design methods/approaches and traditional design methods/approaches 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 rarely consider how to assess and reduce the environmental impact of products, that is why additional eco-design tools have to be integrated in traditional design processes.

2.2.1 Directives and regulations

Many mandatory directives and regulations are needed consider in an eco-design process of lighting products. Main directives and regulations that affect lighting products are explained below, which are needed to adopt in the eco-design process of lighting products:

Energy labelling directive (2010/30/EU) (European Commission, 2010):
This label specifies the lamp energy efficiency class the luminaire is compatible with, and the energy efficiency class of the light source used is specified. The label also specifies information for a LED luminaire with an integrated LED module that cannot be replaced by the end consumer. It also contains the name or trademark of the supplier, the model ID of the supplier (e. g. EAN code), a specification of the supplied or fitted light source, as well as a scale of energy efficiency classes.

Eco-design directive (2005/125/EC) (European Commission, 2005):
The aim of the Eco-design Directive is to reduce (at the design stage) the energy consumption and other negative environmental impacts of products. Although the primary aim is to reduce energy use, it is also aimed to consider other factors that may influence the environmental impact of the product such as materials use, water use, polluting emissions, waste issues and recyclability.

Waste Electrical and Electronic Equipment (WEEE) recycling directive (European Comission, 2008a):
The WEEE directive requires producers and distributors to finance the collection, treatment and recycling or reuse of WEEE. The aim of this directive is to address the environmental impacts of WEEE and to encourage its separate collection and subsequent treatment, reuse, recovery, recycling and environmentally sound disposal. It affects any importer, re-brander or manufacturer of products that requires electricity for its main purpose. These will have to finance the cost of: Collecting, treating (e.g. mercury in lamps, Printed Circuit Board (PCB)), recovering and recycling products imported, re-branded or manufactured.

Restriction of Hazardous Substances (RoHS) directive (European Comission, 2008b):

This directive 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.

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

The aim of this directive is to improve energy efficiency and environmental protection, it applies to products that affect energy consumption throughout their life cycle. This directive does not introduce directly binding requirements for specific product categories, but rather outlines the conditions and criteria relating to environmental characteristics of products, such as energy and water waste, or lifespan, so they can be improved quickly and efficiently. It encourages manufacturers and/or importers to offer products designed to reduce their overall impact on the environment, including the resources consumed during manufacture and disposal. It applies to energy-related products that meet the following criteria: Are sold in high quantities (over 200,000 units/year in the EU), have a significant environmental impact and have a potential for improvement.

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

This directive affects any type of product that uses any type (primary/secondary) of packaging. Its main objectives are: Reduce packaging material excess, eliminate/avoid specific hazardous substances/materials, inform the consumers about the content of product/packaging, reduce the amount of waste at end of life of the packaging, increase/promote the re-use and recycle of packaging waste and inform the producer/manufacturer about their responsibility to recuperate and recycle its packaging.

Lighting is governed by regulations that provide targets to be met in terms of light levels, energy consumption and safety. Regulations do not cover all aspects of lighting, so there are many supplementary guides available for different types of buildings and spaces that fill this gap. There are also some regulations and guides relating to this report, together with other standards and directives affecting lighting is provided on Appendix 1, with a primary focus on the Europe.

2.2.2 Environmental impact assessment tools

Environmental impact assessment tools consider the whole life cycle of systems or products in the assessments. This is necessary in order to assess the environmental impact of materials, processes and activities involved during the whole product life cycle. Then, impacts can be identified and reduction and/or elimination of these implemented. Numerous environmental impact assessment tools have been developed (Finnveden and Moberg, 2005) in order to assess and identify environmental impacts caused by products. There are several types of tools that can assess quantitatively the environmental impact of products. These types of tools are usually based on the LCA method and usually require time and specialized knowledge and skills to apply them, which are reviewed and reported in the following section.

Simapro:
It is a software developed for LCA consultants, engineers and product designers with high/low (depending on version) expertise for highly 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.

GaBi:
It is a software developed for engineers, designers and LCA consultants with high/low expertise (depending on version), for highly (although simplified analysis is also possible) detailed modelling and assessment of the environmental impact of any general product system (product, process or activity) produced worldwide, as the databases have worldwide coverage. It has its own Gabi database, and can have access to industry standard datasets drawn from actual industry processes. It offers fourteen extension databases containing datasets (8,000 datasets), as well as developed ad hoc datasets on components/materials/processes.

Sustainable minds:
It is a software developed for product designers to carry out environmental impact assessment of any type of product produced in America, Asia and Australia (although it can

also be used for estimated results in EU). It has its own database which is based on Impact factors built with Ecoinvent and NREL North American Life Cycle Inventory databases.

Solidworks-Sustainability:
It provides LCA functionality in a CAD software application. It can be considered a 'screening' tool although the databases and environmental impact assessment methods are provided by Gabi (detailed LCA software-based tool). It can provide real-time assessment of the products modelled in Solidworks. The results are shown based on 4 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 this product in Solidworks, which means that product designers that use another CAD software cannot use it. Another disadvantage is that this tool does not allow a complete detailed LCA, and the number of functionalities and assessment possibilities that are possible with LCA software-based tools such as SimaPro or Gabi are not possible.

Some LCA-based software tools are not available in English or they were developed long time ago but have not been updated or are in use anymore, so only tools currently available and updated relevant for product developers have been included in this section. Simapro and Gabi are detailed LCA software-based tools, and Sustainable Minds is a Screening LCA software-based tool. Simapro and Gabi are well-known tools that allow comprehensive detailed environmental impact assessment of products and processes. Both have up-to-date databases and Life Cycle Impact Assessment (LCIA) methods and are available in several languages and versions. These are both recommended for detailed environmental impact assessment for product developers. Sustainable Minds is the only active and up to date screening LCA software-based tool available for product developers at the moment.

2.3 Life Cycle Assessment

One advantage of LCA is that it has an international standard, ISO14040 (ISO, 2006b), which sets out guidelines for consistency of method and interpretation. Useful outcomes of LCA include discovering hotspots within supply chains where the largest impacts occur and tracking improvement over time (Acquaye *et al.*, 2011). LCA is a flexible and transparent tool and using consequential LCA allows the assessment of various scenarios in order to pinpoint changes in environmental impact reductions corresponding to changes.

The literature shows that the Process LCA that follow the International Standard Organisation's (ISO) 14040 four phases: 1) goal and scope definition; 2) inventory analysis; 3) impact assessment and; 4) interpretation (ISO, 2006b).

The Life Cycle Inventory (LCI) is the second phase which involves collection of the background data and which can be time consuming (VROM, 2000). The LCIA is the third phase in which the boundaries and data in the LCI are applied to the specific product or system under review. This can inform decisions such as whether energy use in a factory should be attributed evenly across all the items that were produced or by the number of hours it took to make each specific product. Life cycle interpretation is the final phase during which a summary of the results in the LCIA is given in accordance with the goal and scope definition. In this stage, weighting and grouping can provide a further degree of inconsistency between LCAs (Ahlroth *et al.*, 2011). LCA are used in this research following these standards to quantify the environmental emissions and attempts are made to identify any limitations and drawbacks of the methodologies used.

In order for a company to manage its environmental performance it needs to be able to identify and measure its environmental impact. Depending on industry and companies, different additional needs can occur. Some industries may face political targets or are required to measure specific emissions regarding the specific products, (e.g. toxicity in ICT or GHG in agriculture). This practical factor requires the consideration towards the specific impact associated with the selected product in this research project. Hence, there is need to select indicator/indicators for the system proposed in this research project.

2.3.1 LCA studies related to LED lighting products

The material contents of indicator-type LED components of various colours have been studied by Lim et al. Their leachability tests proposed that the LED components – varying by the colour of the LED – may contain copper, lead, nickel and silver so much that some of the indicator LEDs are classified as hazardous (Lim *et al.*, 2010).

Dubberley et al. analysed the environmental impacts of an intelligent lighting system for commercial buildings in the US. The lighting system consisted of a sensor, wireless network, ballast and batteries. Their main finding was that the potential environmental impacts of an intelligent system are significantly lower (18 to 344 times smaller) compared to a conventional lighting system (Dubberley, Agogino and Horvath, 2004). A fluorescent lamp was the subject of a non-comparative LCA by Techato et al. They calculated the amount of waste from fluorescent lamps and an air-conditioner. The analysis of the fluorescent lamp resulted in a significant amount of hazardous waste compared to bulk waste, but the amount of any type of waste was very low compared to the total weight of the lamp. However, the amount of hazardous waste became relevant when the scope is widened to national (Techato, Watts and Chaiprapat, 2009). The ballasts for fluorescent lamps have been analysed by scholars (Valkama and Keskinen, 2008) (Bakri, Ramasamy and Surif, 2010). Both of the LCAs concluded that the use-stage energy consumption was the major environmental aspect. Valkama and Keskinen stated also that the use of simplified LCA may cause significant changes in the LCA results of the electronic products.

The primary energy consumption for manufacturing of one LED-lamp to 9.9 kWh are also studied (Semiconductors, 2009). The fabrication of the LED-packages has a share of 30%. The LED-chip was fabricated in Germany (frontend) and Malaysia (backend) and the final production of the LED-lamp in China. It was assumed that the production of 1 kWh of electricity requires 3.3 kWh primary energy.

The study calculated the lamp assembly by adding 10% of the production data. Transportation was estimated with 8000 miles (12,875 km) by ocean-going freighter and 4000 miles (6437 km) by light duty truck. The author states the problem that countries with increasing energy efficiency or renewable electricity production tend to outsource the manufacturing emissions to foreign countries with carbon intensive electricity mixes and there is no research about the imported embedded energy of products. This fact leads to distortion of the domestic emission inventories of up to 20% (Quirk, 2009).

The end-of-life of LED lamps and luminaires was studied by Hendrickson et al. They stated that it is possible to reduce the environmental impacts of a solid-state lighting product by implementing design for end-of-life in the product development, e.g., by facilitating the disassembly and enabling the recovery of components, parts and materials to be reused or remanufactured (Hendrickson *et al.*, 2010).

Welz et al. conducted a comparative life cycle assessment study for four different lighting technologies (Welz, Hischier and Hilty, 2011). Although no LED-lamp was assessed, the study results are relevant for this review due to the fact that there are environmental impact results of linear fluorescent lamps. They are rarely compared in comparative life cycle assessment studies on LED-lamps despite of their good environmental performance. The external electronic ballast was included, but the luminaire was not considered. The results of the study show that the manufacturing impact of the linear fluorescent lamp has a share of 8% (Swiss mix) and 2% (European UCTE mix) of the total life cycle impact. Abdul Hadi et al. compared two lamps with a lifetime dependent luminous flux of 25,000 lm–17,500 lm (CMH lamp) and 19,000 lm15,000 lm (LED lamp). These two lamps were considered as equally. The mean luminous flux of the LED-lamp with 17,000 lm is 15% lower than of the CMH lamp with 20,000 lm (GE Lighting, 2011). The study defines that the LED lamp matches the minimum luminous flux of the CMH lamp at the end of the lifetime. Increasing the calculation values of the LED-lamp by 15% to an equal mean level of the CMH lamp, the eco-indicator damage points are close to each other (Hadi *et al.*, 2013).

A life cycle assessment of two lighting technologies based on compact fluorescent (CFL) and Light Emitting Diode (LED) luminaires for the general lighting of the office is studied. The life cycle assessments are carried out considering all the parts of the luminaire: lamp, housing and ballast (or driver for LED). The environmental impact is evaluated considering the whole life cycle of the devices, from manufacturing (including the extraction of raw materials), to use and disposal. An experimental test was conducted to verify the illuminance produced by the two systems. The life cycle assessments show that the LED luminaire allows the environmental impacts to be significantly reduced (reduction of 41% of greenhouse gas emission and cumulative energy demand), mainly due to high energy efficiency in the use stage (Principi and Fioretti, 2014).

This paper undertakes a series of Life Cycle Assessments on two alternative lighting choices (Light Emitting Diodes and Compact Florescent Lamps) under a range of use conditions. It was found that the environmental impacts were comparable for CFLs and LEDs, though significantly less than traditional incandescent, for a range of different use cases. The sensitivity analysis carried out shows that the variation in lamp parameters has a far greater effect on the lifecycle impact rather than the use patterns (Yu, Soo and Doolan, 2016).

GHG emissions of compact fluorescent lamps with linear fluorescent lamps using life cycle assessment method in China's national conditions was studied. The GHG emissions of fluorescent lamps from their manufacture to the final disposal phase on the national level of China were also quantified. The results indicate that the use phase dominates the GHG emissions for both lamps. Linear fluorescent lamp is a better source of light compared to compact fluorescent lamp with respect to GHG emissions (Chen, Zhang and Kim, 2017).

The comparative LCA results showed that, overall, improved luminaire had about 60% or less environmental impact than luminaire with conventional design in all midpoint impact categories in all scenarios, mainly due to the higher luminous efficacy of the improved version. It is estimated that approximately 84 kg of CO 2 could be saved per luminaire per year if the improved version luminaire was used instead of L1 (Casamayor, Su and Ren, 2018).

2.3.2 Social Life Cycle Assessment (SLCA)

LCA is often considered to be a valuable support tool in integrating sustainability into product design and evaluation of products due to its systematic approach. Environmental LCA, hereafter referred as ELCA, is primarily considers environmental impacts along supply chains, from extraction of raw materials to the End-of-Life of products. Social life cycle assessment (SLCA) shares the life cycle perspective with environmental LCA and integrates traditional environmental LCA methodological steps while having social impacts as focus. Similar to ELCA, SLCA adopted the same framework which is comprised of four main steps: goal and scope, life cycle inventory analysis, life cycle impact assessment, and interpretation.

O’Brien et al. first raised the notion of accompanying ELCA with social considerations assessment (O’Brien, Doig and Clift, 1996). Kloffer and Weidema advanced the idea further by proposing ways to integration and alignment of SLCA with ELCA (Klöpffer, 2003; Weidema, 2006). Various indicators have been proposed and implemented, for instance, Quality Adjusted Life Years (QALY) (Weidema, 2006), additional employment (Hunkeler, 2006), and health impacts (Norris, 2006). Dreyer et al. proposed a site-specific assessment where impacts are directly related to company behaviour (Dreyer, 2006).
In 2009, the SLCA guidelines were issued (Benoît *et al.*, 2009). The guidelines are formulated by an open global process involving stakeholders from public, academic, and business sectors. The guidelines are currently the most established and well-used framework for conducting SLCA. It is a framework with guidelines on several approaches, it is by no means an established tool like its ELCA counterpart. Furthermore, SLCA does not determine whether a product should be made, nor does it provide recommendations on addressing any identified social impacts. It only provides a ‘snapshot’ to support decisions on the production of products.

2.3.2.1 Methodology of social life cycle assessment

The assessment boundary of SLCA is set in relation to an Area of Protection (AoP). AoP is indicated to be human well-being in the case of SLCA, which, according to the guidelines, is described as the state of an individual’s life situation. Impacts on human well-being are assessed in connection to five stakeholder groups that are affected potentially. Figure 2-1 illustrates these stakeholders which are worker, local community, value chain actor, society, and consumer (Benoît *et al.*, 2009). It is worth of note that the consumer stakeholder is only included in scenarios of retail interaction, whilst impacts during use phase (the core purpose of a product or service) are not considered. Each stakeholder is associated with a number of subcategories, such as fair salary, working hours, and health and safety for the worker stakeholder, and cultural heritage, local employment, and community engagement for the local community stakeholder. All the stakeholders along with their relating subcategories are presented in Table 2-1 (Benoît *et al.*, 2009).

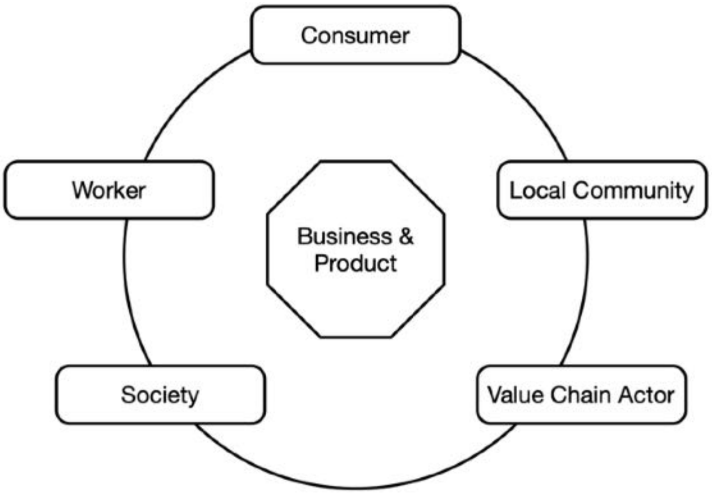

Figure 2-1 Stakeholder groups of SLCA

Table 2-1 Subcategories of stakeholders

Stakeholder categories	Subcategories
Worker	• Freedom of Association and Collective Bargaining • Child Labour • Fair Salary • Working Hours • Forced Labour • Equal opportunities/Discrimination • Health and Safety • Social Benefits/Social Security
Consumer	• Health & Safety • Feedback Mechanism • Consumer Privacy • Transparency • End of life responsibility
Local Community	• Access to material resources • Access to immaterial resources • Delocalization and Migration • Cultural Heritage • Safe & healthy living conditions • Respect of indigenous rights • Community engagement • Local employment • Secure living conditions
Society	• Public commitments to sustainability issues • Contribution to economic development • Prevention & mitigation of armed conflict • Technology development • Corruption
Value chain actors (not including consumers)	• Fair competition • Promoting social responsibility • Supplier relationships • Respect of intellectual property rights

Impact assessment is performed by classifying and characterising inventories into impact categories. in SLCA impact categories are human rights, working conditions, health and safety, cultural heritage, governance, and socio-economic repercussions. The exact relationships and characterisation models between stakeholders and impact categories are not clarified in the guidelines, nor is it the case for subcategories and impact categories (Sala *et al.*, 2015). The generic assessment system from categories to inventory data is illustrated in Figure 2-2.

SLCA can be carried out on two different levels: generic product chain on a general level or actual product chain of specific product. Generic assessments are often carried out to identify social hotspots, which can be used to highlight potential risks of significant negative social impacts and risks to brand reputation as well as identification of opportunities for social improvement (Benoit-Norris, Cavan and Norris, 2012). One can interpret a generic assessment as a top down approach where data are collected from regional, national, and industrial sector levels. Whereas, specific product chain assessment aim to collect data from actual product level, if not product group level. There is one available database for SLCA, namely the Social Hotspot Database (SHDB) (Norris *et al.*, 2011). SHDB mainly contains social data for hotspot assessments on country level and sector level. Only product group data are available for 57 predefined sectors, as data is difficult to obtain at product level.

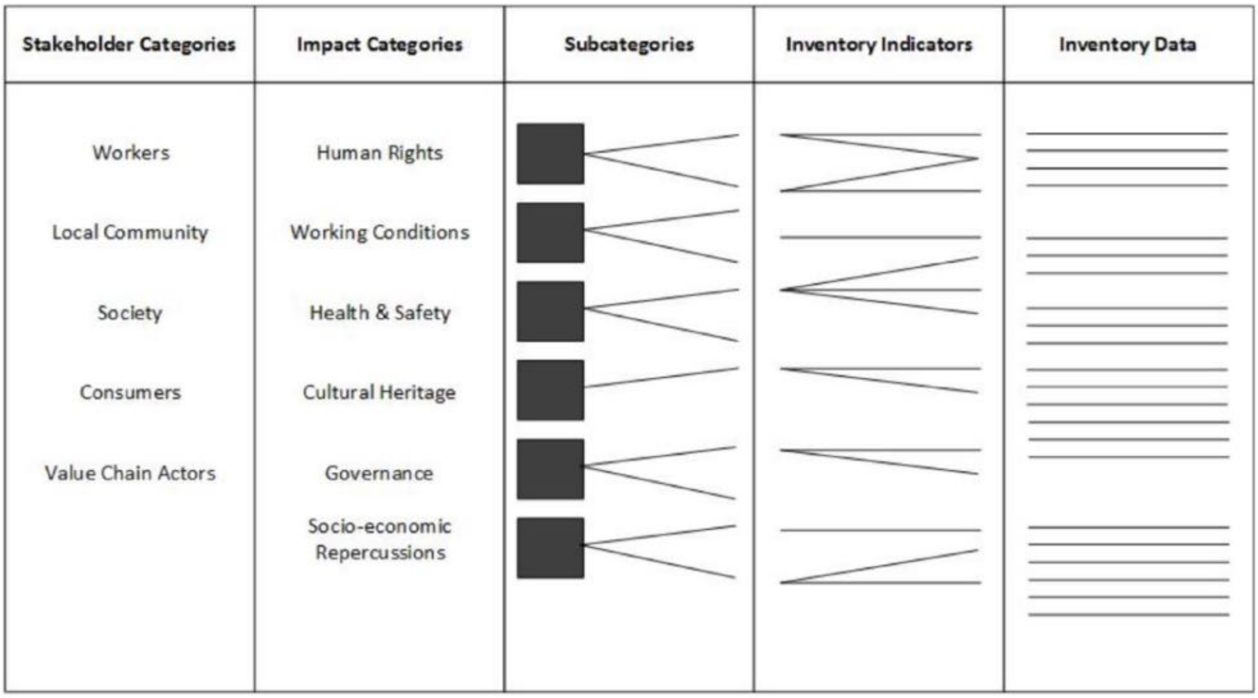

Figure 2-2 Generic assessment system of SLCA impact assessment

2.3.2.2 Two main types of assessment methods

SLCA seeks to assess the potential or real social impacts of a product or service (Chhipi-Shrestha, Hewage and Sadiq, 2015). Social impacts are defined as the impacts on human capital, human wellbeing, cultural heritage, and social behaviour. Currently, there are two main types in SLCA research and practice, namely performance reference point method and impact pathway method.

Performance reference point method: it mainly focusses on living and working conditions of workers, centring on issues such as forced labour, child labour, discrimination and freedom of association or collective bargaining along the life cycle phases (Chhipi-Shrestha, Hewage and Sadiq, 2015). The reference points are usually based on internationally accepted minimum performance levels like the International labour organisation conventions, the ISO 26000 guidelines on social responsibility, and OECD Guidelines for Multinational Enterprises (ISO, 2010)(Parent, Cucuzzella and Revéret, 2010). This method does not assume a causal relationship between processes and the abovementioned conditions, but rather the empirical correlation between the two. This method typically utilises scoring system for the impact subcategories and scoring aggregations for the final stakeholder category score or impact category score. The scoring methods can be two levels (e.g. yes or no, or 1 or 0) (Aparcana and Salhofer, 2013; Foolmaun and Ramjeeawon, 2013) or multi-level (Dreyer, 2006; Hutchins and Sutherland, 2008; Ciroth and Franze, 2011; Ekener-Petersen and Finnveden, 2013). However, the utilisation of subcategories can raise questions regarding whether the subcategories are positive or negative in nature.

Impact pathway method: it assesses the social impacts of products or services. It utilises impact pathways as characterisation models that consists of midpoint and endpoint indicators like environmental LCA (Parent, Cucuzzella and Revéret, 2010). Although some characterisation models have bypassed midpoint categories altogether (Figure 2-3). This method is based upon the causal relationship between processes, for example the relationship between toxic emissions and its consequences on human well-being. There are two typical characterisation frameworks for the impact pathway method: single impact pathway that measures a single social issue, and multiple impact pathways. Past case studies with single impact pathway focused on AoP of human (Feschet *et al.*, 2013)(Hutchins and Sutherland, 2008)(Norris, 2006).

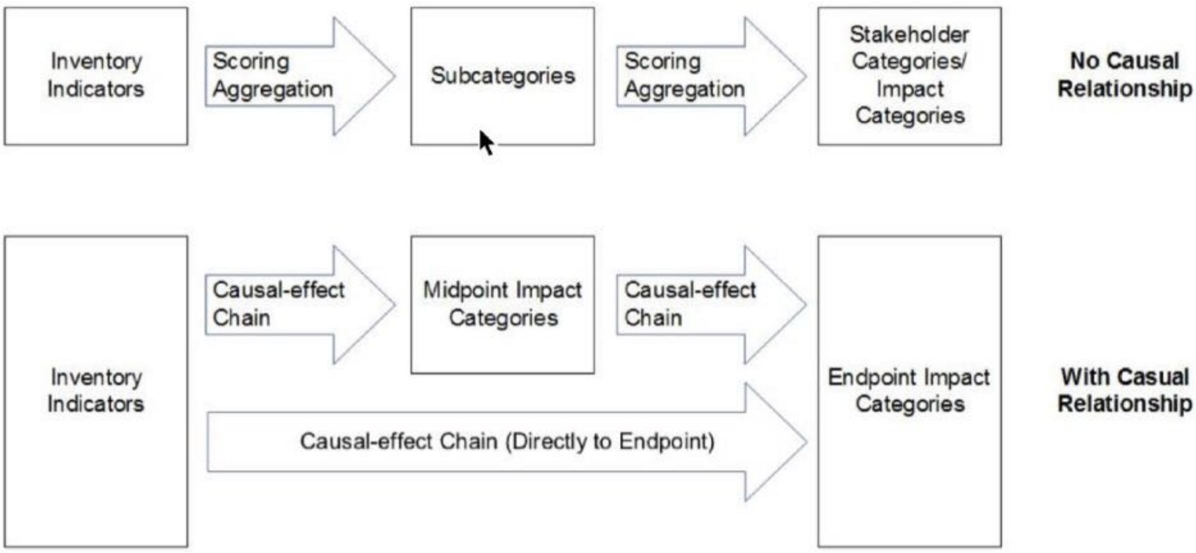

Figure 2-3 Two types of SLCA methods (Wu 2014)

They established the causal relationships between national health improvement (e.g. life expectancy or infant mortality) and economic growth (e.g. GDP). Petti et al. identified 35 publications where SLCA case studies were performed. Of those 35 publications, 68% carried out the case study by using the reference point method, while 6 % implemented the impact pathway method (Petti, Ugaya and Di Cesare, 2014). This does not necessarily equate to the reference point method being better, but rather the impact pathway method is difficult to classify the impact pathways and collect relevant, specific date of a product. it was concluded that the reference point method measures the overall social performance which relates to the relative importance of each context unit over the entire product system (Parent, Cucuzzella and Revéret, 2010). Whereas the impact pathway method measures the social impacts of specific products which relates to the functional unit stated in assessment.

2.3.2.3 Recent studies related to SLCA

A key assertion of this research is the need to assess the positive impacts of products throughout their life cycles. However, there is little consensus on the definition of positive impacts and on methods that incorporate them into impact assessments (Shin, Colwill and Young, 2015). To a certain extent, the development in SLCA embodies the evaluation of positive impacts. In comparison to its ELCA predecessor, which largely considers only negative impacts, SLCA also includes positive impacts relating to social factors (Ekener, Hansson and Gustavsson, 2018). However, these positive impacts are sometimes simply the absence of a negative one. For example, a factory's strategy of not using child labour is considered to be a positive impact, whereas in reality, the elimination or reduction of child labour is really only achieving a neutral or reduced negative impact. While the concept of positive impacts has arisen in recent years, there is still no shared definition of positive social impacts (Sala *et al.*, 2015).

SLCA guideline defines positive impact as impacts that go beyond compliance specified by laws, international agreements and certification standards. This indicates that social benefits/social security issues are only considered positive only under the assumption that they provide additional benefits to the stakeholders. To be precise, this means benefits above the level expected and already given in society. Therefore, positive impacts should cause a 'net gain' in human well-being. Furthermore, similar to ELCA, which SLCA inherited, majority of the researches in SLCA so far mainly focuses on negative impacts or generic hotspot assessment on potential negative impacts. Thence, there are no consensus, well-developed, clear definition of positive impacts and methods that truly incorporate these into impact assessment.

Various ways of addressing positive impacts are identified from reviews of literature. Ekener-Petersen & Finnveden inverted the issue by measuring the lack of/ low level of positive aspects as negative impacts. However, this approach has limitation in identifying positive impacts (Ekener-Petersen and Finnveden, 2013). Benoît et al. expanded this approach by setting performance target points that the impacts are assessed against, thus positive and negative impacts can be determined from the performance target points (Benoît *et al.*, 2009). Ramirez et atl. also adopted this approach, however positive and negative impacts were not distinguished (Ramirez *et al.*, 2016).

A second approach is use by Ciroth & Franze, where negative and positive impacts are rated by assigning values from 1 to 6, (1 for positive and 6 for very negative impacts) (Ciroth and Franze, 2011). This approach is easy to use; however, there are arguable elements such as assessing the lack of forced labour as a positive aspect, whilst this merely put it back to neutral impacts at best. Another approach to address positive impacts is the theory of hand printing, proposed by Norris (2013). Hand printing attempts to measure the positive impacts in terms of avoided negative environment impacts that would have contributed to the environment footprint. While the activities discussed in hand printing involves interactions between individuals and social groups, the fundamental theory is still environmentally linked.

Ekener et al. divides the subcategories in the SLCA guidelines into positive and negative impacts, and suggested tentative indicators for the 12 positive social impacts that were identified (Ekener *et al.*, 2018). However, there is no proposed way to identify, measure, and assess the beneficial user values. While life cycle approach should assess the entire life cycle of products, it can be argued that societal benefits (user values) are the most important social impacts as they characterise the products and fulfil the needs of products. To put it simply, all the other positive or negative impacts should not be made if the products are not fulfilling a need, thus should not be manufactured in first place. Therefore, it is important to assess the benefits of products in particularly during their use phase.

2.4 Characteristic of LED lighting products

2.4.1 Working mechanisms of LED

An LED light source is a small chip comprised of layers of semi-conducting material. LED packages may contain just one chip or multiple chips that are mounted on a heat conducting material called a heat sink and all enclosed in a lens. This LED device can be used separately or in arrays to produce light. LEDs when mounted on a circuit board can be programmed to include lighting controls such as dimming, light sensing and pre-set timing. The circuit board is mounted on another heat sink to handle the heat from all the LEDs in the array. The system is then encased in a lighting fixture or an 'LED bulb' package.

The working mechanism of an LED to produce light lies in the semiconducting material it is made of. An LED consists of a chip made of a semiconducting material. The material is usually doped with some impurities in order to create the P-N junctions, which are made of p-type and n-type semiconductor materials placed in contact with each other. For other types of diodes, current tends to flow easily from the anode or the P-side to the N-side, also known as the cathode. However, this does not take place in the reverse. This process is what makes it possible for the semiconductor to function as a LED (Humphreys, 2008). Holes and electrons, also known as charge carriers, flow into the P-N junction directly carrying different voltages. The moment the electron meets the hole, it falls into a low energy level thus causing it to release some energy. This kind of energy is released in the form of photons.

In the emission of light from an LED, the wavelength is crucial, as it determines the colour temperature of the light produced. The colour of the LED will usually depend on the band gap of the material that is used in the formation of the P-N junction. In germanium or silicon diodes, the holes and electrons recombine through the use of non-radiative transition (Craford, 2008). That being the case, it is important to note that the materials that have been used for the LED will always have a direct band gap such that they have energies that correspond to visible, near infrared, or near ultraviolet lights.

With advances in material science, it has been possible to have other devices with shorter wavelengths and as a result being able to emit different colours of light. Such lights are therefore applied uniquely based on the intended purpose. The LEDs are built mainly on the N-type substrate such that the electrode has been attached to the P-type that is deposited as a layer on the surface. The majority of LEDs used for commercial purposes are known to use different substrates such as sapphire. As discussed above, it is worth noting that the materials used, and the junction determine the light-optical characteristics and therefore applying them accordingly is important in order for the LED to meet the characteristics required for the intended purpose.

2.4.2 LED lamp life

As it would take years to test the real life of LEDs, and by then such products would be surpassed by other LEDs, estimations on LED life are made through laboratory testing. Due to the long expected life of LEDs and their lumen depreciation, the concept of 'Useful LED Life' has been proposed by the Alliance for Solid State Illumination System and Technologies (ASSIST), a group led by the Lighting Research Centre, of Ranssellaer University, New York. This is the point at which light output has reduced to a specific percentage of the original. For decorative applications, this would be L 50 (i.e. time taken until lumens have reduced to 50% of the original). For the case of general lighting, that is more relevant to this thesis, L_{70} is proposed as research has shown that most occupants in an office environment would not perceive a gradual reduction over time of 30% in general illumination (Rea, 2004).

Most manufacturers are quoting lifetime figures of 50,000 hours, or even 100,000 hours (see Table 2-2), but these figures are yet to be measured in the field, hence it is important at this early stage of LED technology to be more cautions on such figures. In any case though, LEDs appear to offer longer lifetimes than existing light sources.

Table 2-2 Lifetime data of LEDs (US DOE, 2009)

Light Source	Range of Typical Rated Life (hours)	Estimated Useful Life
Incandescent	750 - 2,000	
Halogen incandescent	3,000 - 4,000	
Compact fluorescent (CFL)	8,000 - 10,000	
Metal halide	7,500 - 20,000	
Linear fluorescent	20,000 - 30,000	
High-Power White LED		35,000 - 50,000 (or higher by some manufacturers)

2.4.3 Electrical characteristics and quality control

LEDs are very small devices that typically operate at currents less than 1 Amp and low voltages, of 1.5 - 4.0V. As they are such small semiconductor devices, variation in performance due to manufacture is to be expected. Hence all LEDs are tested and grouped based on their performance. The process is called binning. This allows for LEDs to be purchased based on specific performance criteria, with the ones most valued exhibiting the least variation. In the future, with the use of better manufacturing techniques, it is expected that these differences in performance between LEDs will diminish (Gu *et al.*, 2006).

2.4.4 Luminous efficacy

Efficacy of a light source is a measure of how much light is emitted from the source in relation to the input power to the light source. As in the case of other light sources, luminous efficacy is the luminous flux (in lumens) divided by the input power (in Watts), providing a unit of Lumens-per-Watt (lm/W). It is important to note that luminous efficacy is tailored for human vision (i.e. 400 - 700nm of wavelengths), thus any UV or infra-red radiation emitted from a light source is not accounted for. Also, losses due to the efficiency of the LED driver are not taken into consideration. Hence this is very commonly used for rating stand-alone lamps and in this case single, or small packages of LEDs.

For other light sources, standard test procedures are used to rate luminous flux. However, there is currently no industry standard test procedure for rating the performance of LED devices. Typically, manufacturers take measurements both for purposes of luminous flux and colour, which also addresses the binning of LEDs into groups of equal performance, by testing LEDs in a controlled environment of 25 o C and providing a short pulse of power of less than 1 second. This short time is necessary as they are tested without the use of a heat sink, in which case they would immediately fail at longer operating times.

Luminous efficacy values for LED devices provided by manufacturers under the above process can range from 50-120 lm/W, or even higher in some cases. The efficacy of LEDs has been improving every year, meeting targets that had been set and, in many cases, surpassing them. Figure 2-4 shows the progress of LED efficacy over the years and predictions for the future. Figure 2-4 shows that the efficacy of LEDs has seen a dramatic increase in the past few years and the predictions for the future are suggesting a sustained improvement every year. Efficacies achieved in the laboratories are always higher than the efficacies available commercially.

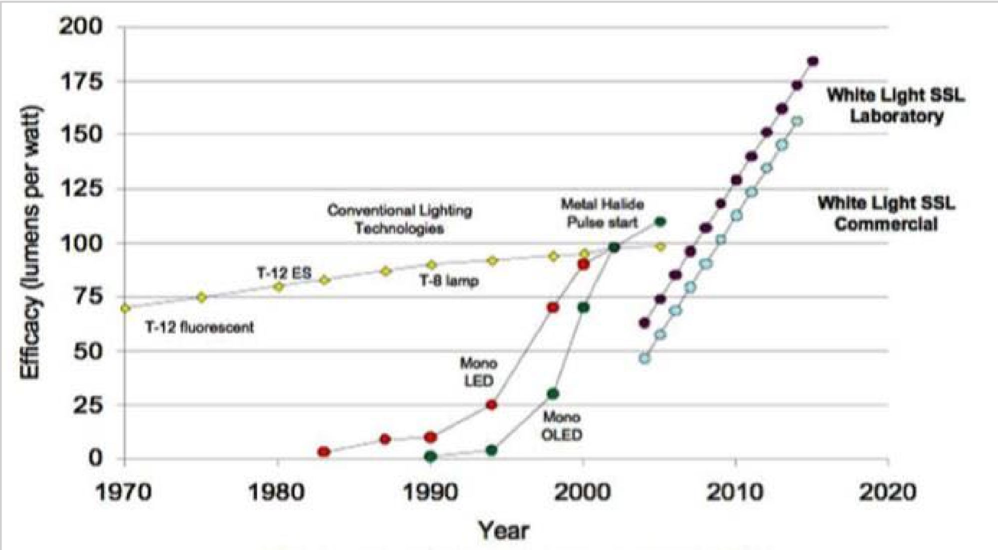

Figure 2-4 US DOE forecast of LED efficacy improvements, relative to current conventional lighting technologies and monochromatic red LEDs and green OLEDs (US DOE, 2014)

2.4.5 Light distribution

Light emitted from most existing light sources has a wide output angle, whereas light emitted from an LED is usually a more focused beam of light. This means that, in the case of a small room, one incandescent or compact florescent lamp would be able to illuminate the whole room whereas, in the case of LEDs, only a small portion of the room would be lit - that to which the LED beam was pointing. In order to illuminate a whole room, multiple LEDs would need to be used, each pointing in different directions. Figure 2-5 shows an example of a typical polar distribution from a commercially available LED, where the directionality of the light source is evident.

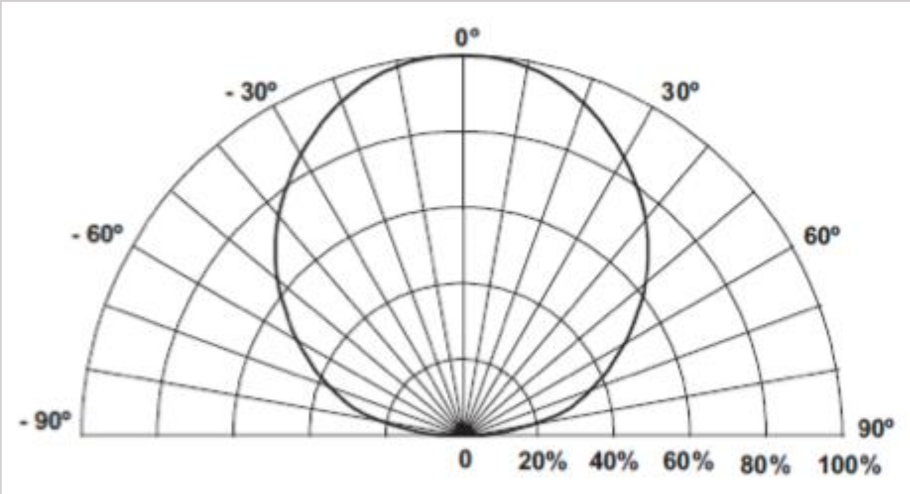

Figure 2-5 Typical light distribution from a white LED (source: Philips Lumileds)

This directionality can also lead to confusion when comparing light sources based on their luminous efficacy. The lumens used to account for the amount of light emitted have no regard to directionality of the light source. Hence when comparing the luminous efficacy of LEDs to other light sources, what is actually being compared is the amount of light directed to the front of each light source.

Taking the example above of a room it is possible to have the same luminous efficacy for all of the light sources, but only some of them managing to illuminate the whole room. Therefore, distribution of the light emitted is an important parameter on optical performance and for LEDs it should be taken into account in conjunction with luminous efficacy.

2.4.6 Dimming

Dimming is a feature that can be very useful in lighting, as it allows for reduced illumination levels and thus reduced energy consumption, when daylight can provide a lot of the light. Dimming equipment for existing light sources is very commonly found in buildings, but this is not necessarily compatible with LEDs.

The electronics of LEDs are often incompatible with the dimmers that were designed for incandescent lighting that are so commonly used, especially in residential buildings. An LED driver, in this case, may be damaged by current spikes or not receive enough power to operate at lower dimming levels. In the case of dimming controls designed for fluorescent lighting though, there is more potential there for LEDs to be used as well, making them more suitable for retrofitting applications.

LEDs can be dimmed by reducing the drive current. The most common LED drivers use pulse width modulation (PWM) to control input power to the LEDs, by turning LEDs on and off at high frequency, varying the total on time to achieve perceived dimming. At frequencies above 120 Hertz, this would not typically be perceived by the human eye. If a dimmer is specifically designed for LEDs, or the existing dimmer has been appropriately matched with the LED driver, dimming is possible down to 5%, or even less (Gu *et al.*, 2006).

For phosphor converted white LEDs a study conducted by Dyble et al. (Dyble *et al.*, 2005), showed very little chromaticity shift when the light output was reduced from 100% to 3%. In contrast, an RGB white LED showed very large chromaticity shifts, over the same range. The technology continues to evolve in this area, but phosphor converted white LEDs which are the focus of this thesis, are already performing well in this area, even when dimmed to a very low level.

2.5 Conclusions of the literature review

This section has reviewed the eco-design process models/methods/approaches, the eco-design tools, and the studies related with the development and market deployment of sustainable LED lighting products available in the literature. All these methods and tools 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 in order to reduce the environmental impact. Therefore, all the process models/methods and tools used in these studies are comprehensive. After reviewing the eco-design process models/methods for generic products and lighting products, it has been noticed a gap of knowledge in models/methods/approaches specific for the eco-design and development of lighting products. Although some of the features of models/methods/approaches to design generic products are also applicable to lighting products, the eco-design of lighting products present particular characteristics that require specific approaches, which highlight the need for the development of an approach to eco-design lighting products.

In addition to this, the models/methods and approaches available not always look at the testing, manufacturing and market deployment stages of the product life cycle, which are necessary for the product developer who has to adopt a life cycle approach in order to reduce the environmental impact of the product. Eco-design tools were also reviewed to find out the advantages and disadvantages of these tools to confirm their suitability in order to be included in the development of an approach to design, test, manufacture and commercialize lighting products with low environmental impact. Different types of eco-design tools for different purposes were reviewed. Some of them were 'prescriptive' such as guidelines, regulations, directives and checklists, and were used to prescribe guidelines. Others were 'analytical' and were used to allow to assess quantitatively the environmental impact of the product. LCA software-based have been reviewed in more detail because they can provide accurate and objective results. The integration of LCA software within the design process has been reviewed and discussed, and it has been concluded that, in general, detailed LCA software-based tools are more suitable for the beginning and end of the design process and screening LCA software-based tools are more suitable for the middle stages of the design process.

Recent studies related to LED lighting products and environmental LCA are also examined. Despite the found differences, the findings of the LCAs were unanimous on two things: the use-stage energy consumption is the most important environmental aspect in the LCAs, and thus, the energy-efficient light sources, such as the CFLs and LED lamps, are more environmentally friendly than their conventional counterparts from the life cycle point of view.

The review of LCA and its recent studies show that LCAs can provide up-to-date information for products, processes and products. Modern society thrives on a diverse and complex economic structure, which makes the acquisition of reliable data even more important and difficult. This chapter also reviewed the social consideration within sustainable design and assessment tools. The concept of positive and negative impacts was introduced, and the importance of such considerations was highlighted. SLCA's historical development was described, its method was expounded, and the two impact assessment methods were explained. Reviews on researches in positive impacts in SLCA were carried out, it was discovered that there is no consensual definition in positive impacts, and methods to assess them varied.

Chapter 3: Research Methodology

3.1 Introduction

This section explains how this research will be conducted in order to achieve the objectives of the research as stated in Chapter 1. It explains the methods and techniques that are used and followed to produce the outcomes of this study.

3.2 Research design and outcomes

1) Development of an integrated eco-design approach:

The first step was to develop an integrated approach to be used as a reference to guide the development of a lighting product with low environmental impacts. In order to create the approach, first it was conducted a critical review and analysis of current eco-design methods/approaches; current eco-design tools; current studies about the design, manufacturing and market deployment of eco-lighting products.

The selection of the relevant issues from these areas, to be used to develop the approach, is based on the review and discussion by other researchers and design practitioners in published material (papers an books) of these topics, and also on the judgement of the author based on trials with these methods and tools during the study, and based on previous professional experience in design practice.

2) Design of the eco-lighting product:

The second step was the design (concept/detail design) of the lighting product with low environmental impact. The design process of the eco-lighting product only focused on how to reduce the environmental impact (with the integration of eco-design tools).

3) Test of the eco-lighting product:

In order to identify suitable lighting simulation software that can accurately predict room illumination from artificial lighting. This was necessary so that the light distribution from luminaires in case study buildings can be accurately predicted. A range of software are reviewed, and selection criteria are put in place. An experiment is then setup in a room so that comparisons between measured and simulated data can be made, which leads to a selection of an appropriate software.

The third step involved testing the lighting product. This step had several objectives: to evaluate and validate the performance of the product, and to pass the required certifications and standards (i.e. IP). The following methods and techniques will be applied: thermal resistance test; Light quality analysis.

4) Test of the web-based eco-deign support toolbox

In addition to the guidance obtained from the review of existing eco-design tools and assessments, these discussions also provided clear support for the novelty of the web-based eco-design support toolbox. It was intended that the integrated eco-design approach would provide a stepwise approach structure to identify required knowledge to build an assessment tool. In addition to the concepts of positive social value assessment of products, a toolbox is also developed to demonstrate how this may fit into a current sustainable practice and aid strategic product management and design for manufacturers. The case study was selected to demonstrate one typical scenario in the lighting product manufacturing industry.

5) Evaluation from the environmental LCA perspective

Environmental LCA will be used to assess, compare and evaluate the developed luminaire. The Goal and Scope stage specifies and defines the functional unit, the system boundaries of the assessment and the assumptions and limitations of the assessment. The LCI defines the inventory of substances contained in the luminaire, the LCIA explains the LCIA method selected and how the substances are assessed, the interpretation of results stage is the stage where results are analysed and interpreted.

More specifically, the following steps will be followed:

- Selection of the benchmark lighting product;
- Full disassembly of the benchmark lighting product and the lighting product developed to obtain the Bill of Materials (BoM) of both products; definition of the functional unit informed by the light analysis;
- Definition of the boundaries of the assessment according to the aim and scope;
- Explanation of limitations and omissions of the data included in the assessment;

- Definition of the LCIA method selected;
- Definition of alternative scenarios to check the sensibility of the results with different likely scenarios;
- Input the Bill of Materials (BoM) previously specified in step 1 into Simapro software;
- Analysis with LCA software and creation of results;
- Display of results (of both luminaires) in tables for interpretation and analysis;
- Design recommendations to further reduce the environmental impact of the assessed lighting products.

6) Evaluation from the social LCA perspective

The LCA framework was selected as a foundation for the development of the social assessment framework for the domestic lighting products. The phases of the LCA framework can effectively encapsulate the key factors highlighted earlier. Relevant social impacts should be identified and listed as a first step in the phase. It is important to capture all the benefits and stakeholders, and impact categories that are related to all the functional inventories, communication with product designers and expert opinions can help to ensure that. Then, the step is classification where the causal relationship between the functional inventories and the benefits are established. These benefits are calculated into indicators for interpretation in the characterisation step.

3.3 Quality analysis for source data used in case studies

All the data used in this research is mainly about the inputs and outputs associated with the LED lighting products. The quality of these adopted data varies considerably depending on the sources, which influences the accuracy of the finalised calculation results. There are three type data sources adopted in this study, and their quality are rated as follows:

- Primary data, if provided by firsthand source directly connected to the analysed case (e.g. the product manufacturer).
- Secondary data, if gathered from informed but not directly connected source to the analysed case (e.g. third-party database; relevant studies).
- Tertiary data, if taken from generic source that are assumed to be equivalent to the analysed case (e.g. governmental departments’ report).

The data sources and their quality assessment rate involved with the products are will be detailed in Chapter 6. The data quality evaluation deserves particular attention and extra efforts, as it affects the accuracy of the calculation results.

Average data are used for the product life cycle inventory modelling. For example, the distance between the manufacturing factory to the retailer shop; average heating time in a manufacturing process. The specific data value is not possibly acquired within the context of this research; hence, the accuracy of the finalised analysis results would be moderated by adopting those average figures. Moreover, aggregating several data sources together for the LCI modelling and LCIA increases the uncertainties for the calculation results, because the methodology used by different databases varies in collecting and compiling their datasets.

3.4 Summary

This chapter introduces the approaches undertaken for achieving the research objectives, which shows the general rationale of conducting this research. Main tools, techniques and testing environments for the LED lighting products are introduced. The advantages of the adopted technologies are also discussed. The last but not least, the source data of the case studies are outlined, and their quality are assessed with three level. The possible limitations associated with the adopted data are also discussed, with the aim of clarifying the directions and targets for future refinement works.

Chapter 4: A Web-based Toolbox to Support Eco-innovation in LED Lighting Products

4.1 Introduction

This chapter presents a Web-based toolbox to assist design engineers for developing Eco-innovative LED lighting Products. The methods analysed the tools information such as prescriptive analytical methods including regulations, directives, standards, CAD software tools/ plugins for LCA analysis / Cost assessment and Hardware tools. Based on the outcome, a web-based toolbox is developed with the required information's and tools. The toolbox provides design engineers a practical means of learning and utilization of necessary tools for developing eco innovative LED products. A case study is presented at the end illustrating the usefulness and utilization of the toolbox.

4.1.1 Demand for the toolbox of led lighting products

LED lighting products have been emerging in the lighting market. They are considered to be the replacement for future lightening (Schwartz *et al.*, 2009; El-Zein, 2013; Kylili and Fokaides, 2015) as a powerful energy saving technology in the globe. About 19% of the total global electricity produced in the world is consumed by lighting products (Waide, Tanishima and Harrington, 2006), and energy consumption has a negative impact in the environment and consumers' cost. It is in fact important to reduce the energy consumed by lighting products where recently LED technology and LED lighting products have received great attention. This is mainly because they can help efficiently reduce energy consumption as well as provide other benefits such as reducing environmental impact and increase performance of lighting products (Waide, Tanishima and Harrington, 2006). Nowadays, there are tools available to develop and manufacture LED lighting products. Design Engineers who play an important role in the process of LED lighting product development need be aware of the available tools, in order to not only successfully produce the products, but also reduce the product's negative impact on the environment.

However, design engineers in LED lighting product manufacturing industries, and SMEs in particular, may be not aware of some of the available tools and may have difficulties to select those tools. These tools can help them to increase reliability, performance, energy efficiency, modularity and recyclability of the LED lighting products. Therefore, it is necessary and demanded by the LED lighting manufacturing industry to develop a toolbox that lighting product design engineers can use to select the tools. The toolbox should not only contain the tools for design and manufacture of the lighting product, but also provide the tools for reducing the product's impact on the environment throughout the product lifecycle, such as elimination of the harmful emission during manufacture, reduction of production waste, recycling rare materials embedded in LED and component/materials reuse. Importantly, the toolbox should also have a learning environment for the designer to learn how to use the tools. However, according to the literature survey conducted by the authors, there has not been such a toolbox available for LED lighting products. To fill this gap, the authors worked with the consortium of the cycLED project supported by the European Commission (cycLED, no date), developed a toolbox to help develop eco-innovative LED lighting products, which is presented in this chapter.

The toolbox is developed using Web technology, with an online self-learning function. During the past few years, many researchers attempted to develop and integrate various tools using a web-based technology. As the web-based technology is very diverse it is necessary to review the existing research works. The forthcoming paragraphs provide a brief overview of the works in the web-based tools usage, technology based online learning environment, and design and manufacture of LED lighting products.

4.1.2 Web technology related to tool integration and technology base online learning

Robin Kay (Kay, 2011) evaluated leaning, design and engagement in web-based learning tools by adopting a method called Learning Object Evaluation Scale for Students. The author also conducted surveys among 834 students and collected data for their analyses. Their results revealed that the constructs for WBLT evaluation scale were internally reliable and demonstrated good construct, convergent, and predictive validity. Kurilovas and Juskeviciene (Kurilovas and Juskeviciene, 2015) reviewed ontology tools for learners to quickly find suitable Web 2.0 tools for their preferred learning activities in virtual learning environment (VLE) by using semantic search engine. They followed a three phased process namely (i) planning (ii) conduction and (iii) reporting. Triangular Fuzzy Numbers method is used to select the best relevant ontology development tool. They also mentioned that the created ontology interconnects VARK learning styles (Visual (V), Aural (A), Read/Write (R), and Kinaesthetic (K)), preferred learning activities and relevant Web 2.0 tools in VLE Moodle.

Kam and Katerattanakul (Kam and Katerattanakul, 2014) created a structural model by applying ground theory approach for a web 2.0 collaborative software. A three-stage coding procedure was followed in their research, namely (i) open (ii) axial and (iii) selective. Then these procedures are evaluated within a team of 3-5 members of 15 groups comprising a total of 65 members. Finally, based on their reports a structural model was formulated for team-based learning.

The importance of Technology based Learning Environments has been analysed by Cavusa and Kanbul (Cavus and Kanbul, 2010). In their study they provided questionnaire and collected the data from a group of 69 students. The study revealed that the most appropriate software having web 2.0 tools which supply students' expectations from TBLE is learning management systems. Kam and Katerattanakul developed and analysed a tool named RSS_PROYECT to effectively produce the RSS feeds. An open source software named 'Joomla!' was used for searching the news related to the exclusion of women in the society. They performed different speed test and confirmed that when the number of feed sources increases, the computational efficiency increases (Kam and Katerattanakul, 2014).

An investigation on the relationship of Web-based data mining tools and business models on strategic performance capabilities has been studied by Heinrichs and Lim (Heinrichs and Lim, 2003). In their work, the impact of using the web-based tools by the worker in an industry is analysed and a business model was developed. They mentioned that to improve the performance and capability of the company, web-based data mining tools is necessary and should be understandable and usable by their workers. An online web-based constraint system to manage the complex configuration requirements for assembly computers is developed by Slater (Slater, 1999). In his work, various possibilities of configurations that can be available for a computer and its integration are mentioned with the help of the tool. Sánchez-Franco proposed a model which link between visual aesthetics, perceived usefulness, non-economic satisfaction and learning performance (Sánchez-Franco *et al.*, 2013). The main aim of the work was to analyse visual design and usefulness on learning and productivity in the domain of web-based tools. Homol compared various web-based citation tools for verifying the accuracy of the results searched by various researchers. He used four web-based citation tools namely EBSCO Discovery Service's Cite tool, EndNote Basic RefWorks and Zotero (Homol, 2014). It has been observed that none of these tools were able to produce accurate citation results for a specified number of test cases.

Isotani et.al developed an intelligent authoring tool using Semantic Web technologies in order to represent knowledge about different pedagogies and practices related to collaborative learning (CL) (Isotani *et al.*, 2013). A pedagogical framework was developed for maintaining a collaborative learning in ontology and to help teachers to create theory-based CL scenarios. Fortmann-Roe developed a web-based, general-purpose simulation and modelling tool to perform modelling and simulation. The work emphasised on System Dynamics, Agent-Based Modelling, and imperative programming (Fortmann-Roe, 2014).

4.1.3 Design and manufacture of LED lighting products

As the present study, focusses on the eco innovation & life cycle analysis which includes environmental impacts, reuse/ recycling, the next few paragraphs are presented focussing these areas. Principi and Fioretti conducted a lifecycle assessment and made a comparative study for Compact fluorescent and Light Emitting Diode (LED) (Principi and Fioretti, 2014). In their work they adopted European Directive 2009/125/EC and 2005/32/EC which focuses on eco-design requirements. Further, the complete product life cycle of the two products are analysed by using SimaPro software. Tahkamo and Halonen presented a life cycle assessment study for high-pressure sodium (HPS) and light-emitting diode (LED) luminaires (Tähkämö and Halonen, 2015). The analysis on eco-friendly street lightning has been performed in accordance with the international standards (ISO, 2006b).

Franceschini and Pansera discussed on unsustainable eco-innovation in lighting sector. They proposed two perspectives namely (i) conceptual map that positions and operationalizes a number of alternative narratives of sustainability and innovation, and (ii) evolution of the lighting sector to show how different narratives may lead to the transformation of the sector. Further to these, six narratives were proposed and discussed on how lighting industry could be improvised especially on thinking beyond LED's and to achieve a real time sustainable eco-innovation (Franceschini and Pansera, 2015). Powers et.al developed a web-based decision support tool named CEAWeb that employs a collective judgment method to gather expert input and find factors which hamper environmental, health, and safety assessments. The tool implemented U.S. EPA's comprehensive environmental assessment approach to prioritize research gaps in areas where new data could make future risk assessments more scientifically robust, and subsequently inform risk management decisions involving emerging materials (Powers *et al.*, 2014).

In addition to these works, there are also some notable research works on eco-design tools (Casamayor and Su, 2013) and future lighting (Vahl, Campos and Casarotto Filho, 2013). These works provide information on various tools available in the LED design and manufacture. Based on these literatures, it is very clear that researchers have adopted web-based tools in assisting engineers, students to improve the quality of learning and improving their business. Many have adopted with different software's for Life Cycle Assessment for LED's and gave some strong insight to future lighting and eco-innovation. Although those tools exist, there has not been a toolbox to integrate the tools together to form a useful information base and to provide a learning environment for designer to develop the LED lighting products in an eco-innovative way, which indicate that the toolbox presented in this chapter is a novel contribution. Also, the literature revealed a strong adaption that the Web-based tools improve the quality of learning and provides a path for eco-innovation. Hence, these research works, it is decided to develop the Web-based toolbox suitable for design engineers to select/utilise suitable tools for eco-design of LED lighting products.

4.2 Structure and contents: recommendations for a flexible and easy to use toolbox

Based on the investigations conducted, it is decided to add the following contents which is considered to be the specification of the toolbox. The toolbox specified will manage resources for the manufacturing of LED product. The toolbox will offer easy access to information on timing, product/component purchasing, cost benefit assessment, LED product specifications, utilization and value for design engineers and production managers /engineers to plan on strategies to implement standards that would result in resources efficiency in the manufacturing of LED lighting product. The tool brings together a collection of hardware instruments, software and utilities that are interlinked to provide cost cutting methods, reducing materials waste and providing good manufacturing practices. Figure 4-1 shows a tree diagram illustrating the developed toolbox which is made up of a collection of system application packages classified under each group.

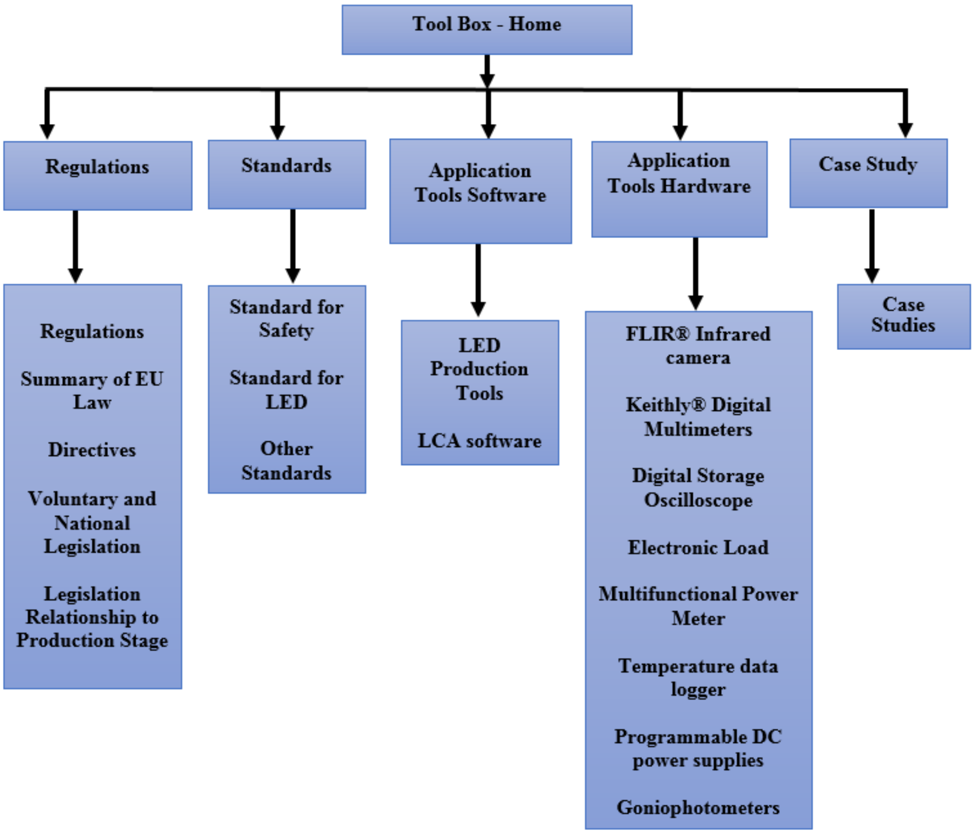

Figure 4-1 Structure of the Toolbox

4.3 Web development of the toolbox

4.3.1 Design: the toolbox structure

The toolbox website has been created to support the various tools that involve the production of LED products. It has been decided to include the following sections which are completely essential in the crux of the website development. They are (i) Home (ii) Regulations (iii) Standards (iv) Application Tools - Software (v) Application Tools -Hardware and (vi) Case Study. In all these sections, it is decided to include all the relevant details with a easy to quick view and having the ability (i) to change images within the design using the File Manager, e.g. rotating images in the header (ii) - to modify the text, in editable 'calls-to-action' or homepage panel(s) to use the 'CSS' or 'HTML' tags (iii) to link the web-based data in the form of 'pdf' or 'doc' files.

4.3.2 Contents and functionalities

The main function of the website is for the end user to aware various standards, regulations, directives, software and hardware tools for increasing resource efficiency and reducing environmental impact from production of LED products. It opens up with a homepage and gives importance how the toolbox can be utilized by the users. Once the user navigates through the regulations page, the site provides the information on five topics namely (i) regulations (ii) summary of EU law (iii) directives (iv) voluntary and national legislations and (iv) legislation relationship to production stage. Under each category the details that are related to the topics are given and are summarized as follows: (i) regulations giving a brief overview available to the present LED manufacturing. They are (i) EC 244/2009: Eco-design - Lamps Implementing Directive 2005/32/EC of the European Parliament and of the Council with regard to eco-design requirements for non-directional household lamps (ii) EC 1194/2012: Eco-design (recast) - lamps Implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to eco-design requirements for directional lamps, light emitting diode lamps and related equipment and (iii) EC 347/2010 (amendment of EC 245/2009) The eco-design requirements for fluorescent lamps without integrated ballast, for high intensity discharge lamps, and for ballasts and luminaires able to operate such lamps. In the subpage 'summary of EU law' under regulations the details of EU law are provided and followed by the directives in the consecutive subpage. The page of voluntary and national legislation and legislation relationship to the productions stage gives the details of the various legislations available and applicable in the LED manufacturing industry conforming to EU standards.

4.3.2.1 Regulations

Regulations are the most direct form of EU law - as soon as they are passed, they have binding legal force throughout every Member State, on a par with national laws. National governments do not have to take action themselves to implement EU regulations. A regulation is similar to a national law with the difference that it is applicable in all EU countries. The list of regulations that are applicable to the current scenario is as listed in the Table 4-1.

Table 4-1 Regulations Applicable to the Current Scenario

Regulation	**Common reference (acronym)**	**Title description**
EC 244/2009	Ecodesign - lamps	Implementing Directive 2005/32/EC of the European Parliament and of the Council with regard to ecodesign requirements for non- directional household lamps
EC 1194/2012	Ecodesign (recast) lamps	Implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for directional lamps, light emitting diode lamps and related equipment
EC 347/2010 (amendment of EC 245/2009)	Ecodesign – (FL lamps)	The ecodesign requirements for fluorescent lamps without integrated ballast, for high intensity discharge lamps, and for ballasts and luminaires able to operate such lamps

Directives - EU directives lay down certain end results that must be achieved in every Member State. National authorities have to adapt their laws to meet these goals, but are free to decide how to do so. Directives may concern one or more Member States, or all of them. Directives set out general rules to be transferred into national law by each country, as they deem appropriate. The list of directives that are applicable to the current scenario is as listed in the Table 4-2.

Table 4-2 List of Directives Applicable to the Current Scenario

Directive	Common reference (acronym)	Title description
2005/32/EC	Ecodesign Directive - EuP	Establishing a framework for the setting of ecodesign requirements for energy-using products (EuP)
2009/125/EC	Ecodesign Directive (recast) ErP	Establishing a framework for the setting of ecodesign requirements for energy-related products (ErP) (Ecodesign recast)
2012/19/EU	WEEE (recast)	Waste electrical and electronic equipment (WEEE) (Text with EEA relevance)
2004/108/EC	EMC	Electromagnetic Compatibility Directive as amended by Directive 92/31/EEC
2006/95/EC	LVD	Low Voltage Directive (LVD)
2011/65/EC (recast)	RoHS	The restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS) recast
98/11/EC	Energy Labelling Directive	Energy labelling of household lamps Directive (where applicable).
2010/30/EU	Energy Labelling Directive	The indication by labelling and standard product information of the consumption of energy and other resources by energy- related products
2002/91/EC	EPBD	the energy performance of buildings
2001/95/EC	Product Safety	General product safety

Decisions -Decisions are EU laws relating to specific cases. They can come from the EU Council (sometimes jointly with the European Parliament) or the Commission. They can require authorities and individuals in Member States either do something or stop doing something and can also confer rights on them. A decision only deals with a particular issue and specifically mentioned persons or organisations.

Voluntary & National Legislation: The complete list of the voluntary & national legislation with their html link to their respective websites are given in the Table 4-3.

Table 4-3 Voluntary & National Legislation

Reference	Common reference (acronym)	Title description
COM (2008) 400	GPP	Green Public Procurement - Public procurement for a better environment
EC 66/2010	Ecolabel	The EU Ecolabel

Table 4-4 indicates the relevance to each stage of the production process for identified legislation. There remain uncertainties as to the potential influence of many legislative mechanisms, and the significance of the interrelation of alternate product components (optic, control, mechanical etc.) on the optimisation of the whole product system! Indication of relevance:

- Primary relevance (red) - the production aspect of direct relevance to the intended outcome (area of influence) of the legislation (i.e. reduced energy consumption provides focus on the electronic component specification.
- Secondary relevance (orange) – the additional production aspects relevant to the legislation (i.e. optic specification influence on energy consumption).
- Tertiary relevance (green) – limited influence on the production aspect.
- Uncertain (white).

Table 4-4 Indicative relevance of Legislation to production phase

Legislation	Name	Material specification	Optics specification	Electronic specification (driver, LED)	Mechanical specification	Sub- assembly	Final Assembly (Luminaire)	Testing
2005/32/EC	Ecodesign Directive -EuP							
2009/125/EC	Ecodesign Directive -ErP							
2012/19/EU	WEEE (recast)							
2004/108/EC	EMC							
2006/95/EC	LVD							
2011/65/EC	RoHS							
98/11/EC	Energy Labelling							
2010/30/EU	Energy Labelling (recast)							
2002/91/EC	EPBD							
2001/95/EC	Product Safety							
COM (2008) 400	GPP							
EC 66/2010	Ecolabel							

4.3.2.2 Standards

In essence, a standard is an agreed way of doing something. It could be about making a product, managing a process, delivering a service or supplying materials – standards can cover a huge range of activities undertaken by organizations and used by their customers. Standards are the distilled wisdom of people with expertise in their subject matter and who know the needs of the organizations they represent – people such as manufacturers, sellers, buyers, customers, trade associations, users or regulators. Standards are knowledge. They are powerful tools that can help drive innovation and increase productivity. They can make organizations more successful and people's everyday lives easier, safer and healthier.

UL8750-2009: Light Emitting Diode (LED) Equipment for Use in Lighting Products:
Organization: Underwriters Laboratories (UL) an independent product safety certification organization based in Northbrook, Illinois, US. Edition Date: 18/11/2009. This document covers the LED part which is an integral part of the luminaire or other lighting equipment operating in the range of 400-700nm.These requirements also cover the component parts of light emitting diode (LED) equipment, including LED drivers, controllers, arrays, modules, and packages as defined within this standard.

IES LM-82-12: Characterization of LED Light Engines and LED Lamps for Electrical and Photometric Properties as a Function of Temperature
Organization: The Illuminating Engineering Society of North America (IESNA). Edition Date: 13/02/2012. The new standard is designed to establish consistent methods of testing and data presentation to assist luminaire manufacturers in selecting LED light engines and integrated lamps for their luminaire products. This approved laboratory method defines the procedures to quantify the performance of LED light engines and integrated LED lamps as a function of temperature.

JESD 51-51: Implementation of the Electrical Test Method for the Measurement of Real Thermal Resistance and Impedance of Light Emitting Diodes with Exposed Cooling

Organization: JEDEC Solid State Technology Association Edition Date: 12/04/2012. This document provides information on thermal test requirements (static test methods) for the measurement of real thermal resistance and impedance of LED (Power LED's and High brightness LED's) with exposed cooling surface. The purpose of this document is to specify, how LED's thermal metrics and other thermally-related data are best identified by physical measurements using well established testing procedures defined for thermal testing of packaged semiconductor devices (published and maintained by JEDEC) and defined for characterization of light sources (published and maintained by CIE – the International Commission on Illumination).

IES LM-80-08: LED Lumen Maintenance of LED Light Sources

Organization: The Illuminating Engineering Society of North America (IESNA) Edition Date: 22/09/2008. The purpose of LM-80-08 is to allow a reliable comparison of test results among laboratories by establishing uniform test methods. It addresses the measurement of lumen maintenance testing for LED light sources including LED packages, arrays and modules only. It does not provide guidance or recommendations regarding prediction estimations or extrapolations for lumen maintenance beyond the limits of the lumen maintenances determined from actual measurements.

IES TM-21-11: Lumen Maintenance Life Test Projection

Organization: The Illuminating Engineering Society of North America (IESNA) Edition Date: 25/07/2011. This document recommends a method for projecting the lumen maintenance of LED light sources from the data obtained by the procedures found in IES document LM-80-08 Approved Method for Measuring Lumen Maintenance of LED Light Sources. LED light sources provide a very long usable life but light output gradually depreciates over time. TM21-11 provides the method for determining when the “useful lifetime” of an LED is reached, a point when the light emitted from an LED depreciates to a level where it is no longer considered adequate for a specific application. Lumen maintenance of LEDs can vary from manufacturer to manufacturer and between different LED package types produced by a single manufacturer.

NEMA SSL-1-2010: Electric Driver for LED Devices, Arrays and Systems

Organization: The National Electrical Manufacturers Association (NEMA). Edition Date: 28/02/2011. This standard provides specifications for and operating characteristics of nonintegral electronic drivers (power supplies) for LED devices, arrays, or systems intended for general lighting applications. Electronic drivers are devices that use semiconductors to control and supply dc power for LED starting and operation. The drivers operate from multiple supply sources of 600 V maximum at a frequency of 50 or 60 hertz.

NEMA White Paper Lsd-45

Organization: The National Electrical Manufacturers Association (NEMA) Edition Date: 03/09/2009. This document provides guidelines on solid state lighting sub assembly interface for luminaires – guidelines does not apply to LED retrofit lamps. This new white paper, prepared by the NEMA Solid State Lighting Section, covers the design and construction of interconnects for solid-state lighting applications. It compiles the latest industry information regarding mechanical, electrical, and thermal connections and documents existing industry best practices

IES LM-79-08: Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products

Organization: The Illuminating Engineering Society of North America (IESNA) Edition Date: 31/12/2007. This approved method describes the procedures and precautions for performing reproducible measurements of total luminous flux, electrical power, luminous intensity distribution and chromaticity of solid-state lighting (SSL) products for illumination purposes under standard conditions. Covers LED-based SSL products with control electronics and heat sinks incorporated. It does not cover external operating circuits or external heat sinks (e.g., LED chips, LED packages, and LED modules). Uses absolute photometry rather than relative photometry (historically the lighting industry standard) for the measurement of SSL.

IES TM-25-13: Ray File Format for the Description of the Emission Property of Light Sources

Organization: The Illuminating Engineering Society of North America (IESNA) Edition Date: 2013 TM-25-13 provides recommendations for a standard ray file format to describe the emission properties of light sources. The ray file format contains information necessary to interface between ray tracing or other optical design, simulation, analysis and metrology software used in lighting applications.

IEC/PAS 60598-1 Edition7.0

Organization: International Electro technical Commission (IEC) Edition Date: 2008 1 of International Standard IEC 60598 specifies general requirements for luminaires, incorporating electric light sources for operation from supply voltages up to 1 000 V. The requirements and related tests of this standard cover: classification, marking, mechanical construction and electrical construction.

IEC/PAS 62722-2-1 Edition 1.0: Luminaire performance - Part 2-1: Particular requirements for LED luminaires

Organization: International Electro technical Commission (IEC) Edition Date: 01/06/2011 The first edition for a performance PAS for LED luminaires for general lighting applications acknowledges the need for relevant tests for luminaires using this new source of electrical light, sometimes called “solid state lighting”. The publication is seen in close context with simultaneously developed and edited publication of performance standards (or PAS) for luminaires in general and for LED modules. Changes in the LED luminaires PAS will have impact on the module standards and vice versa, due to the behaviour of LED. Therefore, in the development of the present PAS, mutual consultancy of experts of both products has taken place. The provisions in the standard represent the technical knowledge of experts from the fields of the semiconductor (LED chip) industry and of those of the traditional electrical light sources and luminaires.

IEC 60838 ed4.2

Organization: International Electro technical Commission (IEC) Edition Date: 16/06/2011 Part 1 version of this document provides information on general requirement and test for miscellaneous lamp holders. The IEC 60838-1 applies to lamp holders of miscellaneous types intended for building-in (to be used with general purpose light sources, projection lamps, floodlighting lamps and street-lighting lamps with caps) and the methods of test to be used in determining the safe use of lamps in lamp holders. This part of IEC 60838 also covers lamp holders which are integral with a luminaire. It covers the requirements for the lamp holder only. The technical content is therefore identical to the base edition and its amendments and has been prepared for user convenience. It bears the edition number 4.2.

IEC60838-2-2 Edition 1.1: Part 2-2: Particular requirements – Connectors for LED-modules
Organization: International Electro technical Commission (IEC) Edition Date: 01/04/2012
Part 2 version of this document provides information on particular requirement of connectors for LED modules.

4.3.2.3 Application Tools Software

A brief overview of the LCA software tools is provide in Table 4-5. Five popular LCA tools, including CES EduPack, Solidworks Sustainability tool, Sustainable Minds, SimaPro and Gabi are included. It covers different LCA categories, with assessment goals ranging from basic ones (carbon footprints and energy consumption) to a list of 17 mid-points impact and three endpoints (human health, eco-system and resource); embedded assessment methods ranging from single one to 15 comprehensive ones. The tool categories include online tools, LCA embedded in engineering material databases, CAD packages, and stand-alone specialized LCA tools.

Table 4-5 Application Tools (Software)

Packages	Definition of product and lifecycle	Presentation of results
CES EDUPACK	Data input via tables	• Information with carbon and energy • Results presented via bar and pie charts plus data sheets
Solidworks sustainability	• Product is defined via 3D CAD models • Lifecycle data entered via tables and pull-down manue	• Relatively detailed information available • Results presented via pie charts, tables and the CAD model
Sustainable Minds	Data input via tables	• Relatively detailed information available • Results presented using pie charts and data sheets • Impact distribution of different parts
SimaPro	• Data input via tables • Lifecycle is defined via structured framework and the network based on the life cycle framework	• Detailed information available • Results are presented via network framework, tables and bar charts • Comparison function between two products
Gabi	Product is defined through a user-friendly lifecycle builder in a graphical way	• Detailed information available • Results are presented via lengthy tables with limited graphic presentation, not very user friendly.

4.3.2.4 Application Hardware Tools

During the development and manufacturing of LED-modules some Hardware Tools are needed. The Tools are necessary to calculate, to improve engineering figures, technical specifications and to test the target systems. The manufacturers are using a variety of different Hardware Tools. Most of important Tools are described below. The Tools were proposed and presented by the SME’s and then discussed by the project consortium members. The list of tools used to describe in this report are presented in Table 4-6. They are (i) FLIR (ii) Keithly (iii) Digital multimeter (iv) Digital storage oscilloscope (v) Electronic load (vi) Multifunctional power meter (vii) Temperature data logger (viii) Programmable DC power supplies and (ix) Goniophotometers.

Table 4-6 Application Tools Hardware

Hardware	Purpose of the Product	Remarks
Infrared camera FLIR® (manufacturer)	With infrared cameras you get a thermal picture of the viewed area and detect in detail the hotspot and the source of heat	Through IR-camera it's easier to detect hotspots and they give a better overview.
Digital Multimeters Fluke, Voltkraft, Mannesmann (manufacturers)	Standard tool for all measurements in the electric and electronic field. Multimeter shows usually only the current value of this parameter	A multimeter will be connected to the points of interest in an electric circuit in line or parallel, depending on the parameters that are measured and on the circuit properties and conditions
Digital storage oscilloscope Fluke, Cesys, Voltkraft (manufacturers)	Standard tool for the measurement of many electrical and electronic parameters.	An oscilloscope will be connected to the points of interest in an electronic circuit with a probe head which has a high resistance.
Electronic load (multiple manufacturers)	Creates the condition for the function of an electronic device. Without a load, it makes no sense to develop a device.	It is the fundamental base in electronic devices, because it determines the handicaps and main topics for the development.
Multifunctional power meter + net quality analyser; Fluke, Voltcraft, manufacturers)	Power meters measure the power consumption of a device.	The power meter will be installed in the main power line. All parameters will be measured and displayed in several ways.
Temperature/data logger(multiple manufacturers)	Stores the values in selectable time spans, by special triggering or by changing. Analyzing the logged data, give you an idea about the thermal environment of a running device.	By using detector pads having different detection temperature it is possible to identify the maximum temperature reached over a longer period without additional energy.
Programmable DC power supplies (multiple manufacturer)	To test components with fixed conditions and high precision like constant voltage without disturbing influences in the power source.	Depending on the test procedures it is not always necessary to use a programmable power supply.
Goniophotometers	Performs the measurement of the spatial distribution of a radiation source and displays the photometric properties of the light visible to the human eye in relation to a defined angular position	The automotive and general lighting industries use goniophotometers for lighting research and as a control measure in their manufacturing workflow.
Optotransmitter-Umweltschutz-Technologie e.V (OUT).	OUT provides set of Hardware Tools required for LED lightning measurement and tests, including Optical Measurements, Electrical Measurements Mechanical Analyses, etc.	http://www.out-ev.de/english/technical-services/optical-measurements.htm

4.3.3 Testing the Toolbox website in different browsers

The Web-based Toolbox is constructed to be viewable in a number of browsers and across multiple platforms. Certain browsers can display pages in different ways, which can cause problems with some designs. As a minimum the site should work in line with the signed off design for the latest and previous version of the following browsers Internet Explorer (v8 and v7) Mozilla Firefox (v3.6 and v3) Google Chrome and Safari (v5, 4 and 3). The site is also tested to ensure that it works in older browsers such as Internet Explorer 6 but there is no guarantee that it will look exactly the same as in the signed off design. After the site is completed certain parts of it are validated to check that it is correct. The following will be tested: (i) HTML Validation: - Using the following link the primary parts of the site will be checked to ensure they have zero errors in them. This will include the home page and any other pages which use a different template such as listing pages. http://validator.w3.org/ (ii) CSS Validation - Using the link below all the style sheets for the site will be checked to be error free. There are at least 3 style sheets for the site, one for layout (layout.css) one for the style of the text and links (style.css) and one for displaying the site when it is printed (printer.css). http://jigsaw.w3.org/css-validator/. Security is provided at two levels: The website administration area (CMS) is having an operating system security applied to it using apache and ht access. Usernames and passwords will be created by Nottingham Trent University. There will be no facility for the client to amend these themselves. The website will be tested to ensure that certain areas of the site can only be accessed by the administrators. The following security checks are be performed: (i) the admin area can only be accessed using a username and password. (ii) the log files area can only be accessed using a username and password. Screen shots of the developed Toolbox site is shown in the Figure 4-2 and Figure 4-3.

Figure 4-2 Screen shot of the Front page of the Toolbox Website

Figure 4-3 Screen shot of the Software Tools page of the Toolbox Website

4.4 Concluding remark

In this chapter, an eco-design support toolbox has been successfully developed with various tools for assisting design engineers to develop eco innovative LED lighting products. The toolbox contains the regulations, directives, standards, and software and hardware tools used in the LED lighting product industry. The Web-based toolbox is now fully functional. A case study illustrating the application of the toolbox within the development of eco-lighting product, ONA LED table lamp, will be presented in the following Chapters.

Chapter 5: The Integrated Approach

5.1 Overview of the integrated approach

The approach developed by this research integrates various eco-production tools/methods into the LED product development process, as illustrated in Figure 5-1.

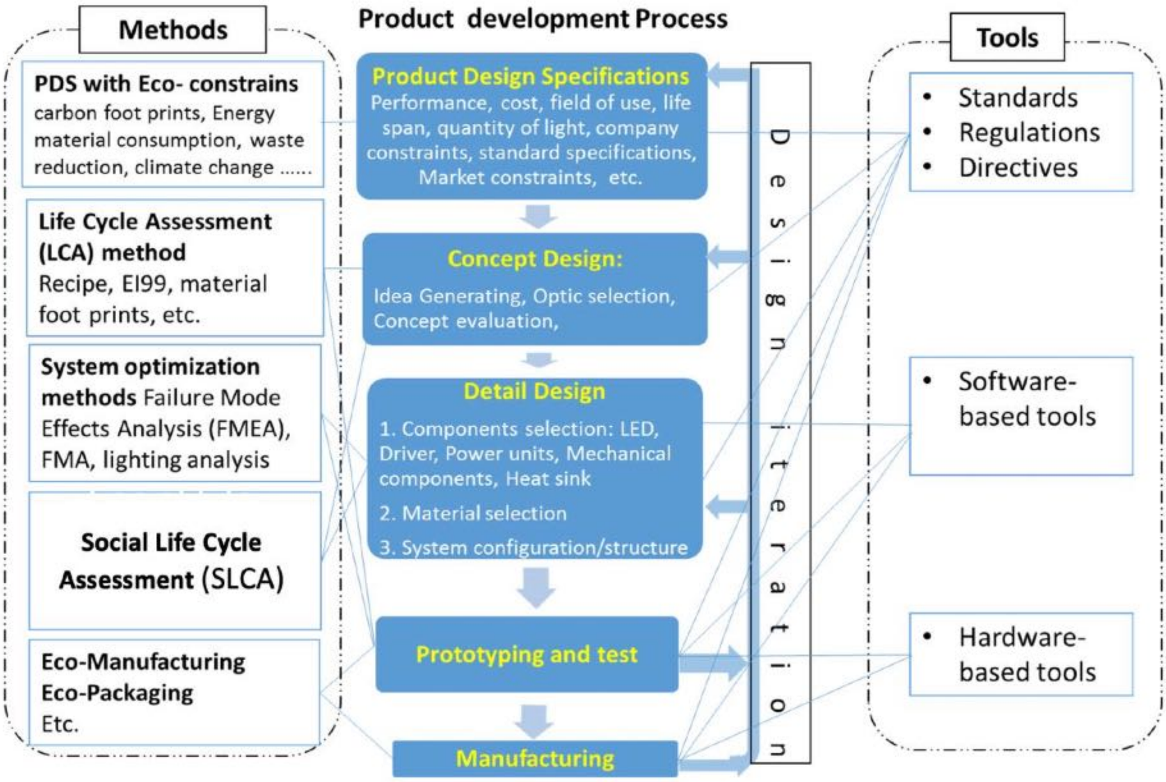

Figure 5-1 The integrated approach

5.1.1 The methods and tools considered in the integrated approach

The eco-production methods might include:

- Elaboration of product design specifications with eco-constrains, such as reduction of product carbon footprints, energy/material consumption, waste, and contribution to climate change, etc.
- Product lifecycle impact assessment methods (e.g. ReCiPe, CML).
- Product failure analyses, such as failure mode and effect analysis, and failure mode effect and criticality analysis, etc.

- Eco-design methods, such as modular design, design for re-use, design for recycling, etc.
- Eco-manufacture, eco-packaging, etc.

Resulted from the cycLED project, an eco-production toolbox has been developed, which can be utilized in the product development process. The categories of the tools include:

- Regulations, including the regulations related to eco-design lamps, as well as directives, voluntary and national legislations, for example, directive 2012/19/EU 'Waste electrical and electronic equipment (WEEE)'(European Comission, 2008b). Currently this category includes 15 tools in the toolbox.
- Standards, for example, standard 'UL8750-2009: Light Emitting Diode (LED)' Equipment for Use in Lighting Products' (UL, no date). This category currently includes 13 tools in the toolbox.
- Application tools (software) are software-based tools for selection of LED chips and lifecycle assessment software packages, such as SimaPro (PRé, no date). Currently this category includes 7 tools in the toolbox.
- Application tools (hardware) are the equipment used to ensure quality of the LED lighting products, for example, goniophotometer (RADIANT, no date). Currently this category includes 9 tools.

5.1.2 The product development process considered in the integrated approach

The product development process considered include the elaboration of Product Design Specification (PDS), conceptual design, detail design, prototyping and test, manufacture, as illustrated in Figure 5-1.

In the PDS elaboration phase, the eco-constrains are derived from various sources such as relevant directives, regulations, eco-design guidelines, standards, etc. These eco-constrains are integrated into the PDS. In the conceptual design phase, to meet the PDS formulated in the previous phase, several design concepts are generated, and then evaluated against the PDS evaluation criteria. Relevant standard is used to set-up the evaluation criteria. LCA will be conducted during the concept design stage, and, in so doing, relevant LCIA methods such as: ReCiPe, material footprints, carbon footprints, etc. will be utilized. Because in the conceptual design phase, the product information is not very detailed, unlike the detail design phase, a quick estimation is preferred, LCA software for simple and fast analysis, such as Sustainable Minds (Sustainable Minds, no date), is more suitable.

In the detail design phase, the product is further developed from the concept obtained in the conceptual design phase. The major tasks to be conducted include selection of components (LED chips, heat sink, LED driver, etc.), material selection, and the product system configuration. Several software tools will be utilized to help to select the components and conduct the detail design task. Relevant standards are also referred during this stage of the process to ensure the product quality and to meet the eco-specifications.

In the prototyping and testing phase, the prototype of the product will be produced and tested, and relevant eco-manufacture/eco-packaging methods will be utilized in order to ensure the product to meet the required eco-constrains and the product quality according to the referred standards. Proper testing equipment will be utilized to test the product quality. The LCA methods, eco-design methods and product failure analysis methods are all utilized in this phase. Unlike the simple/quick LCA conducted in conceptual design phase, a more comprehensive LCA is conducted at this stage. A suitable LCA software such as Simapro ((PRé, no date) is utilized to conduct more detailed analysis. This is because, in this phase of the product development, the product prototype is completed and hence more detailed information about the product is available.

The prototyping and test are further detailed in Sections 5.2 and 5.3 below. In the manufacturing phase, relevant eco-manufacturing and eco-packaging methods are applied to reduce waste, material, energy consumption, and impact on the environment. Relevant standards are also followed at this stage to ensure product quality.

5.2 Prototyping and testing

In this phase, the manufactured prototype will be tested and analysed to confirm that the final real product could pass all the tests and standards required. In so doing, software-based tools, hardware tools, and test/testing methods were used. To illustrate how the hardware tools and software tools will be used in this phase, the light analysis (using goniometer) and the environment impact assessment (using LCA software) will be introduced in the following sections. The prototype of the design table lamp is presented in Figure 6-1 Initial architecture of the product', see Chapter 6.

Type of tests/analysis involved

- Luminaire efficacy test: The efficiency and efficacy of the electronic components, sub-systems and whole luminaire will be tested, measured and analysed.
- Energy consumption test: The measurement will be taken after a 30 minutes-period to allow stabilization of the light source and lighting system energy consumption, and it will be measured using a plug-in power meter.
- *Light analysis test*: The Light performance of the luminaire will be measured and analysed.
- *Disassembly test*: The luminaire is easy to dismantle, only a screwdriver is required, and it takes around 5 minutes to take apart the main parts and components.
- *Environment impact assessment*: The environmental impact of the luminaire will be measured and analysed.

Software-based analysis tools utilized

- ProSource (RADIANT, no date): This software can process the data captured by the goniometer, and translate it into EULUMDAT and IESNA photometric files that can be exported and analysed in Photometric analysis software. The light performance of the prototype was analysed to obtain the photometric files and calculate the efficacy of the luminaire. Photometric files ultimately provide the light distribution of the luminaire, which can help to reduce the energy consumption. If the light distribution is known, the light output of the luminaire can be used more efficiently.
- Photometrics Pro (Photometric.com, 2015): This software can analyse the data contained in EULUMDAT and IESNA photometric files and translate it into graphs-results which shows the light performance (light distribution, light intensity, beam angle, etc.) of the luminaire. After using the goniometer and ProSource software to obtain the EULUMDAT and IESNA files, these were used in Photometric Pro to analyse the light parameters and performance of the luminaire.

- Simapro (PRé, no date): This software is used to assess the environmental impact of the luminaire. The prototype was dismantled, and all the materials and substances weighted, and its values input into the software for analysis. The results of the assessment showed the total environmental impact of the luminaire, each life cycle stage, and each process and material used. This information was used to know which product life cycle stage and components had higher impact to inform possible further eco-design improvements to reduce the impact of the luminaire. Since this is not the final manufactured product the assessment results cannot be used (externally) to inform consumers, to support Environmental Product Declarations (EPD), or for benchmarking.

5.3 Hardware-based measurement tools utilized

- Source meter: This is a tool used to measure the energy efficacy of the LED, LED driver and LED-LED driver system, among other functions. Once the LEDs and LED drivers were selected based on several criteria: energy efficacy, compliance with RoHS, reliability and serviceability; these were tested with a source meter to confirm the energy efficacy of each component, and to find out the energy efficacy of the LED-LED driver system. The efficiency of the driver was 80.4%, and the efficacy of the LED-LED driver system was 112 Lm/W, which is a good value.
- Goniometer: This tool is used to capture and measure the photometric data from the luminaire. The light performance of the prototype was measured using the goniometer, and photometric files (EULUMDAT and IESNA) produced using ProSource software.
- Illuminance meter: This tool is used to measure the illuminance of the luminaire in lux. This value is necessary to carry out the analysis with the goniometer and obtain the photometric files. The illuminance of the prototype was calculated when the luminaire was mounted on the goniometer previous to conduct the full light goniometer analysis.
- Colour meter: This tool is used to measure the Correlated Colour Temperature (CCT) in Kelvin (K) of light sources or luminaires. The CCT of the luminaire was measured as part of the light analysis. CCT measurements are required because the colour

temperature of the luminaire may differ from the one provided by the light source supplier when the light source is used within the luminaire whole system. The luminaire function is to provide a specific light quantity and quality because both parameters affect the energy used and the lifespan of the luminaire. For example: If the CCT degrades below certain levels, the function of the luminaire may not satisfy the user needs and hence the luminaire will be disposed.

- Power meter: This tool is used to measure the energy consumption of the luminaire. The energy consumption of the prototype was measured before the light analysis with the goniometer. The measurement was carried out after 30 minutes of functioning in order to allow the luminaire consumption to stabilize.

5.4 Concluding remarks

An integrated approach for sustainable lighting product development is presented in this chapter. The approach integrates various sustainable tools and methods into the lighting product development process including product design specification, conceptual design and detail design, prototyping and test, and manufacture. This chapter gave an overall presentation of the integrated approach. Further detailed presentation are given in other chapters: the tools to be considered in the approach are presented in Chapter 4; the conceptual and detail designs, prototyping and testing are detailed in Chapters 6 and 7. The important life cycle assessment methods, environmental LCA and social LCA, utilised in the design of the lighting product, are further detailed in Chapters 8 and 9.

Chapter 6: Sustainable Lighting Product Design

In order to examine the quality of the designed lighting product, the following section introduces the overview of the integrated eco-design approach and the parameters of the designed product. In addition to this, to compare and evaluate the environmental impact and product optical performance between the designed lighting product with the existing commercial product. Utilisation of the integrated approach to develop an eco-lighting product the integrated approach has been utilised to develop a lighting product, which is detailed int this section. The product is manufactured by Ona product L.S.(Spain).

6.1 Configuration of Product Design Specifications (PDS)

The following PDS with eco-constrains (eco-PDS) are specified during PDS configuration phase:

- The product should use as a smaller number of components as possible, whilst maintaining the required quality.
- Extend the product lifespan. The product should be durable, and components should have easy access for repair.
- To apply eco-design methods, such as modular design, design for easy repair and upgrade, design for disassembly, design for reuse.
- Design and implement systems (related with the product) that facilitate components and luminaires' recovery for re-use, re-manufacture and recycle.
- Use the minimum type of materials, which facilities the sorting of components for reuse and recycling when the product reaches its end of service life.
- Avoid: The use of special tools for disassembly, non-detachable joints (welded or glued joints), labels attached the product, finishes in materials, and toxic materials.
- Use low environmental impact materials and manufacturing processes.

The above PDS are derived from relevant directives, regulations and standards related to sustainable development. For example, the 'Restriction of Hazardous Substances (RoHS) directive' restricts the use of six hazardous materials: Lead (Pb), Mercury (Hg), Cadmium (Cd), Hexavalent chromium (Cr^{6+}), Polybrominated biphenyls (PBB) and Polybrominated diphenyl ether (PBDE), in the manufacture of various types of electronic and electrical equipment. Derived from this directive, the 'avoid using toxic materials' is specified in the PDS, and all the electrical and electronic components (LEDs, driver, circuit, etc.) used in the demonstrator comply with RoHS.

6.2 Conceptual design

In the conceptual design phase, the product concept was developed in compliance with the eco-PDS and relevant regulations and directives.

Compliance with the eco-PDS

- Use less components: The product is made of 3 main housing parts, and the architecture of the product is quite basic and simple, which make it easy to dismantle for repair, re-manufacture or recycle.
- Increase product lifespan: Several strategies have been implemented to increase the product lifespan: 1) Increase the reliability of the product, 2) design the product for easy disassembly, 3) long warranty, 4) Use recyclable materials, 5) design a system to incentive return of products, 6) Register with WEEE to facilitate recycling and 7) informing the consumer how to use and where to dispose the product for recycling.
- The product should be easy to repair and upgrade: The product has a basic architecture with few parts which facilitates disassembly. It does not use non-detachable joints so the product can be dismantled and repaired without breaking the product (non-destructive disassembly). It can be dismantled with a standard screwdriver.
- Use standard components and provide product structure information with suppliers' name and component ref. to consumers to facilitate repair and upgrade outside the warranty period.
- Use recycled materials: The main materials used in the product are aluminium and PMMA. The aluminium is 100% recycled.
- Easy access to components for repair: Access to electrical-electronic components that may fail or get out of date is easy, and only one screwdriver is needed for disassembly.

- Improve the energy-efficiency of the product system: The LED driver has been selected to optimally function with the LED, to save energy and extend lifespan. Energy-efficient light sources have been used.
- Use the minimum type of different materials: The number of materials used in the product have been reduced to 2 main materials (in the housing) for easy separation.
- Use recyclable materials: The main (with the highest weight %) material used in the product is 100% recycled aluminum.
- Design for disassembly: The product has a basic architecture with three main parts which facilitate disassembly. It uses eight screws that can be dismantled to have access to all internal components without breaking the product (non-destructive disassembly). It can be dismantled with a screwdriver.
- Avoid the use of (special) tools for disassembly: The only tool required for disassembly of the product is a screwdriver.
- Avoid non-detachable joints (welded or glued joints): All the joints used in the product are detachable, so the product can be dismantled without breaking it (non-destructive disassembly).
- Avoid the use of labels: Labels are not used in the product and the packaging, which facilitates recycling of the materials.
- Avoid the use of finishes on the materials: The materials used have no additional coating, which facilitates recycling.
- Reduce the weight and volume of the product and packaging: The volume of the product is quite small, and the total weight is 601 g. This contribute to reduce the impact caused during distribution. The geometry of the product also facilitates to pack more products within the same volume, which also reduce the impact in the distribution stage.

Compliance with eco-regulations and directives

- Energy labelling directive (2010/30/EU): The packaging of the luminaire provide information about energy consumption, light output performance, and useful lifetime of the light sources used (European Commission, 2010).
- Waste Electrical and Electronic Equipment recycling (WEEE) directive: The company has been registered with a WEEE recovery and recycling scheme (European Comission, 2008b).
- Restriction of Hazardous Substances (RoHS) directive: The product and all the components included comply with RoHS directive (European Comission, 2008a)
- The Eco-design directive (2009/125/EC): The LED driver-LED system has been optimized to save energy, and Energy-efficient light sources have been used. In terms of materials, the lifespan of the product has been extended, it has been designed the product, so it is easy to dismantle to facilitate repair, re-use, re-manufacture and recycling. Recycled materials have been used, that are recyclable (European Council, 2009).

6.3 Detail design

In the detail design phase, the eco-PDS, directives and standards are followed, and relevant software is utilized to develop the lighting product.

Compliance with the eco-PDS

Due to limitation of space, only selected eco-PDS are mentioned in this sub-section:

- Specify reliable components from well-known suppliers: LEDs and LED drivers have been outsourced from well-known suppliers (Samsung supplied the LEDs, and Lumotech supplied the LED driver), and the models selected have passed reliability tests.
- LEDs specifications: LED chips: Samsung LM561A - 5630 Middle Power LED
- Driver specifications: Lumotech: LEDlight Micro series - L05050/L05150
- The driver feature a series of properties that contribute to extend its lifespan (and the whole luminaire): Open circuit protection, overload, over voltage and over temperature protection, high power factor (0.91), Future-proof flexibility: industry leading output voltage range enabling seamless support of LED generations and

minimizing supply chain complexity. The warranty is 5 years (around 50,000 operative hours), in order to match the LED long lifespan (50,000 h.).

- The LED chips have passed reliability tests and are PB free and comply with (European Comission, 2008a).
- Reduce the number of joints: The product only has 3 joints to join the 3 main parts (diffuser, structure heat sink, and structure cover). These parts are joined by pressure-fit.
- Reduce the type of joints: The joints used do not require specific tools, to make disassembly easier.
- Integrate functions: One of the main parts of the structure, which is made of aluminium, also functions as heat sink. This is an example of integration of 2 functions from 2 components in one component.
- The product should be easy/fast to disassembly: The initial structure (Figure 6-1) of the product was revised and optimized to reduce the number of disassembly steps, joints and components. Screws have been eliminated and all the parts are now assembled by pressure-fit.

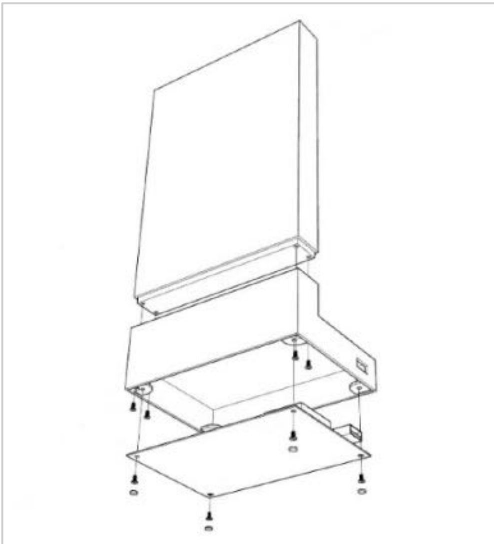

Figure 6-1 Initial architecture of the product

<u>Compliance with the standards</u>

Standards: Components (LEDs, drivers, heat sinks, etc.) specified to suppliers should have passed the highest standard possible. The following standards are utilised:

- British standards CE, EN55015 (BSI, 2013a), EN61000-3-2 (BSI, 2014a), EN61347-2-13 (BSI, 2014b), EN61347-1 (BSI, 2013b), EN61547 (BSI, 2009), EN62384 (BSI, 2006):

These standards are related with reliability and safety of drivers. Some of these are required to comply with the basic CE label for devices that have to be commercialized in EU, and others specify performance requirements that can be over the standards required. The LED driver selected (Lumotech LEDlight Micro series - L05050 / L05150) comply with all the standards mentioned above and present some advanced features which makes the driver (and hence the whole lighting system) more reliable and longer lasting. Advanced features: Short and open circuit protection, overload and over voltage protection, Safety Extra Low Voltage (SELV), future-proof flexibility: Industry leading output voltage range enabling seamless support of LED generations and minimizing supply chain complexity.

- IES-LM-80 (IES, 2008a) and IES-TM-21 (IES, 2011): These are standards and methods for testing the estimated lifespan of LEDs. LEDs have to be outsourced from suppliers that provide lifespan data based on these standards in order for the results to be reliable and comparable with other suppliers. The LEDs selected (Samsung LM 561A – 5630 middle power LED) provided performance datasheets based on these standards.

Utilization of software tools

The following software tools are utilised to select/design the components of the product:

- LED-driver selector on-line web-based tool (Future Lighting Solutions Inc., 2015): The driver selector tool helps to choose the optimum driver type (in terms of performance) according to specific LEDs performance. Once the brand and general type of components (LEDs and driver) were selected, It was selected the specific performance (model) of each type of component (LED and LED-driver) based on the results of this tool to optimize the energy efficacy of the LED-LED driver system.
- KiCad EDA suite software suite (Kicad EDA, 2015): Kicad is a software used to design schematic diagrams and Printed Circuit Boards (PCB). The LED chips used are standard, but the LED- strip created is not. This LED-strip PCB was designed using Kicad suite software.
- Thermal resistance datasheets: Thermal resistance datasheets were used to guide heat sink design and dimensions. The aluminium-made extruded heat sink initially designed by ONA was improved and optimized in a second iteration using the

thermal resistance datasheets and the experience of external consultants. These changes were carried out to optimize the thermal performance of the heat sink.

6.4 Lighting products utilized for demonstration of the integrated approach

Product A: The designed table lamp

Figure 6-2 shows the designed LED table lamp designed by utilizing the integrated approach is manufactured by the ONA product SL. The aim of this redesign is to increasing resource efficacy and reducing environmental impact of LED lighting product, take into consideration of easy disassembling after end of life, use Eco friendly material. The main materials used are PET and Aluminium. 50% of the product is made of recycled materials: The aluminium used in the housing and heat sinks is recycled. The product presents a simple structure with four main parts that can be disassembled fast (20 seconds, as specified by ELPRO GmbH recycle centre) and easily without special tools by recycling companies. The technical specifications of the redesigned lamp are shown in Table 6-1.

Figure 6-2 The designed LED table lamp

Table 6-1 Technical specifications of designed LED table lamp

Items	Amount
Weight (g)	734
Luminous flux luminaire (Lm)	400
Luminaire efficacy (Lm/W)	71.4
Power consumption of luminaire (W)	5.6
Color Correlated Temperature (CCT) (˚K)	4000
Color Render Index (CRI)	80
Luminaire useful lifetime (h)	93000 (L70)

Figure 6-3 and Figure 6-4 respectively shows the disassembled part and components of this table lamp.

Figure 6-3 Driver components of the redesigned table lamp

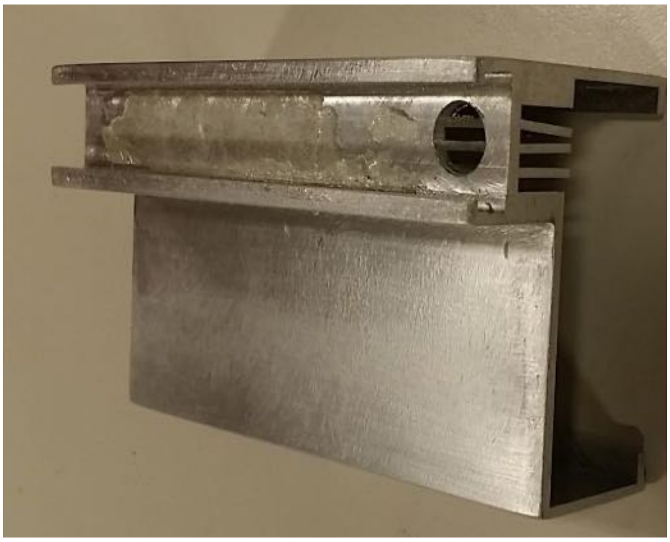

Figure 6-4 Base of the redesigned table lamp

Table 6-2 shows the benchmark product and product BoM (bill of material)

Table 6-2 BoM of benchmark product

Material	Weight [g]
Mixed cables/wires	66
Aluminium	78
Aluminium Profile	132
Plastics white	374
ferrous scrap	4
Components containing precious metals	14
PWB class 1 (LED PWB)	8
PWB class 2	58
Total:	734

Table 6-3 Shows the BoM of the designed LED table lamp

Table 6-3 BoM of the redesigned LED table lamp

Material	Weight [g]
Mixed cables/wires	24
Aluminium Geschirr	242
Plastics white	192
ferrous scrap	2
PWB class 1	6
PWB class 2	74
Total:	540

Product B: A common table lamp from current market which has similar lumen.

Figure 6-5 shows a normal LED table lamp, which is currently available in ONA product catalogue. This product in this research is used as a benchmark product in comparison with the new product shown in Figure 5-5.

Figure 6-5 LED Table lamp B

Philips LED light bulb Product information:

Kelvin: 2700K

Lifetime (Hours) :15000

Lightbulb Shape: Classic

Lightbulb Type: LED

Lightbulb Wattage: 6W

Lumens: 470

The Experimental test has been conducted by utilising the tools mentioned above and detailed in Chapter 7. The environmental LCA and social LCA are conducted using SimaPro and openLCA, which are future detailed in Chapter 8 and Chapter 9.

6.5 Conclusions

This chapter offered an approach for the design, manufacturing and market deployment of eco-lighting products in particular, and there is not such an approach in the current literature. Although there are approaches and methods to eco-design products, these have been developed to eco-design 'generic' products, and do not take into account the particular characteristics of any specific category of products such as lighting products. A novel up-to-date eco-design method to eco-design lighting products has been developed and used base on the integration of specific eco-design tools such as eco-design guidelines, regulations/directives, LCA software-based tools, testing tools and light analysis tools at a specific time during the design and development process. The designed lighting products present particular 'environmental impact patterns' in specific life cycle stages and components, and also require specific types of methods, tools and eco-design strategies to assess their environmental impact, and reduce/eliminate these impacts.

Chapter 7: Experimental Investigation of the LED Lighting Product

7.1 Evaluating the optical qualities of the lighting product

7.1.1 Optics criteria

Optics is an important field in physics used to study the behaviour of light, including how different materials interact to produce different forms of light. This section will deal with the optical characteristics of the designed eco-lighting product. More specifically, it will deal with the light output of the product in terms of quantity of light, distribution of light and colour characteristics. Other aspects such as dim-ability and control will also be considered.

A wide range of lighting simulation software exist on the market. A lot of them only deal with daylight whilst others deal only with artificial lighting, and there are some that deal with both. For this study, a range of criteria were put in place to test and select appropriate lighting simulation software, as detailed below:

- Accuracy of results in predicting room illumination from artificial light sources;
- Ability to model a physical environment ranging in geometry, from the scale of a whole building, to a room;
- Ability to define fluorescent and LED luminaire lighting specifications from existing luminaires in the market and predict lighting performance in a space;
- Ability to provide rendered images of results;

7.1.2 Overview of selected tools

RADIANCE: It is a freely available radiosity-based lighting simulation program that uses a backward ray-tracing process for simulation. It was developed by Lawrence Berkeley Laboratory and its accuracy in lighting simulation is well established as it has been validated. Radiance requires the 3D geometric information of a model to be provided as a text file, usually derived from other software. Radiance is capable of handling complex geometries and there are no limits imposed by the software on what can be modelled. In this work, the geometric setup of the software was provided by ECOTECT which is a building simulation software that is part of the Autodesk suite of products. This software provides a comprehensive exporter for RADIANCE and also allows the importing of RADIANCE results back into ECOTECT for visualisation. Furthermore, it allows for the specification of custom grid points for calculating lux levels in a room and it is not bounded by any geometrical limits.

DIALux: It is a freely available and widely used package in lighting design. This program specialises in interior lighting and uses the POV Ray rendering engine to produce photorealistic images and provides outputs in PDF format. DIALux imposes some limits on the type of geometry and can be created on imported, thus limiting the usability of the software for more complex geometries.

Relux: It is used for both interior and exterior lighting simulations. This software uses RADIANCE as the calculation engine and can produce a photorealistic image output through its sister product, Relux Vision. It has the ability to generate geometry through its own object library or import geometry from other software.

AGI32: It is a lighting simulation tool by Lighting Analyst that can perform daylight and artificial lighting simulations. This lighting simulation software has integrated ray-trace and radiosity-based calculation engines to produce light data output and photorealistic images. It has the ability to generate complex geometries or import 3D geometries from other software.

7.1.3 Experimental setup and implementation

In order to compare the lighting software, it was decided that software predictions should be compared with measured data in a real room and hence a real office room was selected for this experiment. Light measurements were taken and then compared to the software simulation results. This section describes in detail the experimental setup used.

A room space was needed that would allow for easy access for a range measurement throughout the experimental period and also included a suspended ceiling with fluorescent ceiling tile type luminaires (see Figure 7-1).

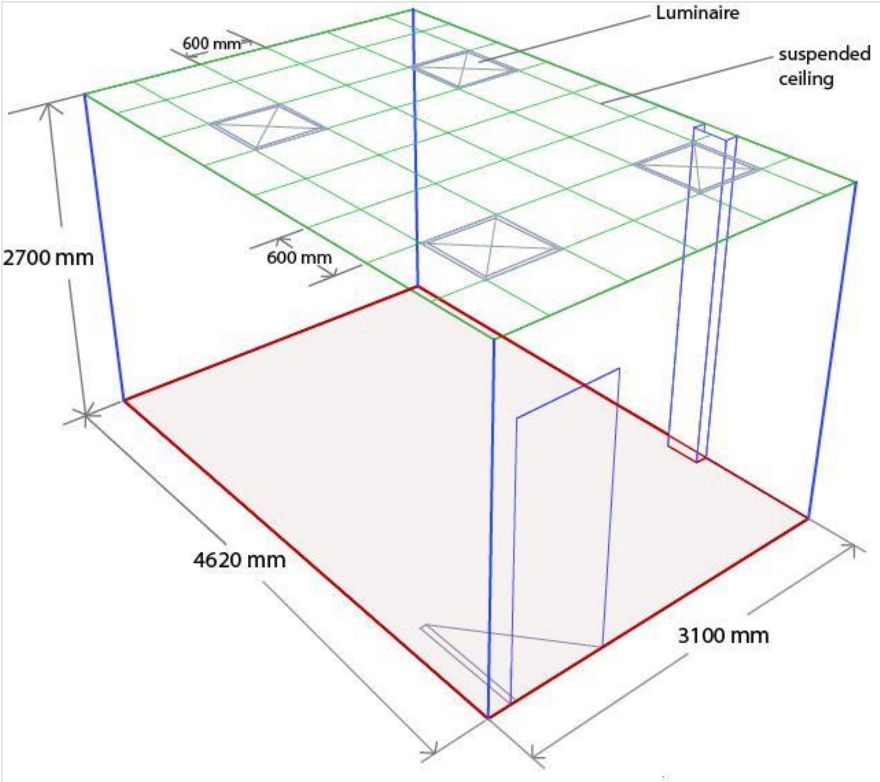

Figure 7-1 Test room model

Figure 7-2 Luminance meter used for determining reflectance of surfaces

The geometry of this room was replicated in all lighting simulation software under investigation. In order to perform lighting simulations, the reflectance of each surface had to be determined in order to be used as input in the software.

Reflectance for all surfaces in the room (walls, floor, ceiling) were obtained using the Konica Minolta LS-110 luminance meter (Figure 7-2). This spot luminance meter with and angle of view that has been categorized in the highest range of DIN quality class B, which is considered one of the highest in the market, and is capable of measuring dark surfaces with a beginning range of 0.001 cd/m 2 and has the ability for user calibration.

These devices were positioned on a custom-made stand, which held the meters at the specified height of 800mm from the floor throughout the measurements. This provided a stable position for measurements to be taken. Any movement of the meter, if held by hand, could potentially alter the angle at which measurements were taken and hence influence the results. Care was taken during measurements, so that no obstructions that could shade the meter would be present above 800mm, which meant that the person taking the measurements had to lie on the floor. A series of pre-marked positions were set in the room, so that the whole stand can move to precise locations within the room and thus obtain measurements at the pre-defined grid.

In all lighting simulation software, the same room geometry was replicated and a grid of points of the same dimensions as the one used for site measurements was specified so that lux levels could be predicted for comparison. In all software, appropriate settings of high accuracy were used, so that comparisons could be made between them and the measured data. A list of settings used for each software can be found in Table 7-1. The following section presents and discusses the results of this study.

Table 7-1 Lighting software settings used for simulations

Software	Software setting used in the simulations
RADIANCE	• Indirect Reflections: 5 • Model detail, Variability, Image Quality: High • rtrace -I -h -dp 2048 -ar 32 -ms 0.063 -ds .2 -dt .05 -dc .75 -dr 3 -sj 1 -st .01 -ab 8 -aa .1 -ad 512 -as 256 -av 0.01 0.01 0.01 -lr 12 -lw .0005 -af
DIALUX	Calculation options: very accurate; Calculation method: standard
RELUX	• Precision: High indirect fraction • Raster: 0.7 • Active Dynamic Raster: on, fine • Maintenance factor: 0.85
AGI32	• Calculation mode: full • Radiosity Convergence: Maximum Steps: 1000 • Stopping Criterion (Convergence): 0.01 • Display Interval: 10 • Maximum Subdivision Level: 5 • Minimum Element Area: 0.0465 m2 • Element Luminance Threshold: 1.5

7.1.4 Optic experiment analysis

Figure 7-3 - Figure 7-5 show a comparison of results for measured and four simulated sets of data. Three graphs are presented, each one showing data points for three positions in the room. Positions A(1-15) for a series of data points on one side of the room close to the wall, positions E(1-15) for a series of data points at the centre line of the room and positions I (1-15), for a series of data points along the other side of the room, close to the opposite wall.

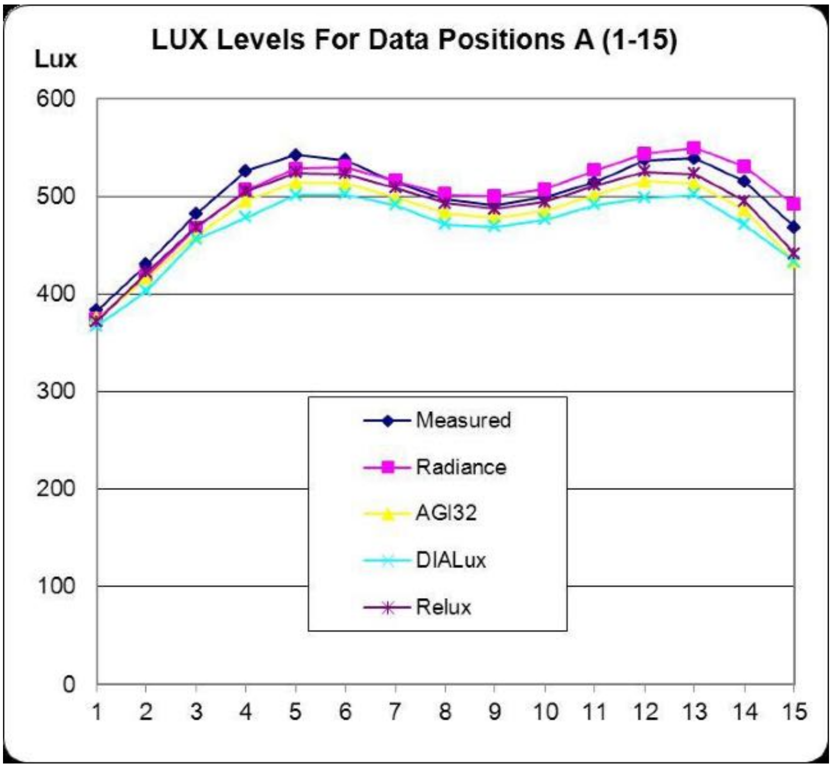

Figure 7-3 Comparison of measured and simulated illuminance data for 4 lighting simulation packages, for data series A

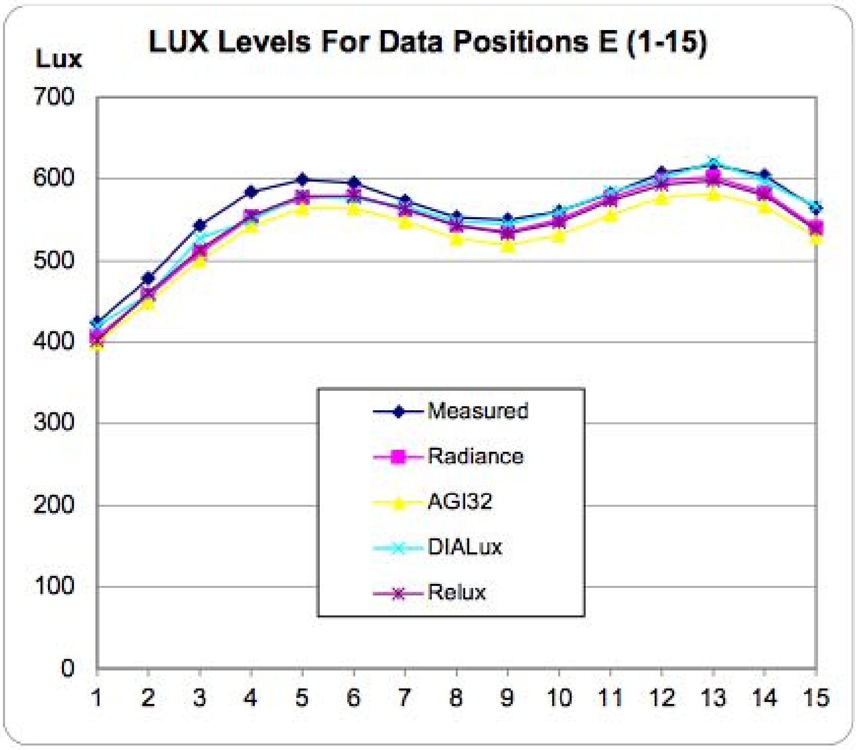

Figure 7-4 Comparison of measured and simulated illuminance data for 4 lighting simulation packages, for data series E

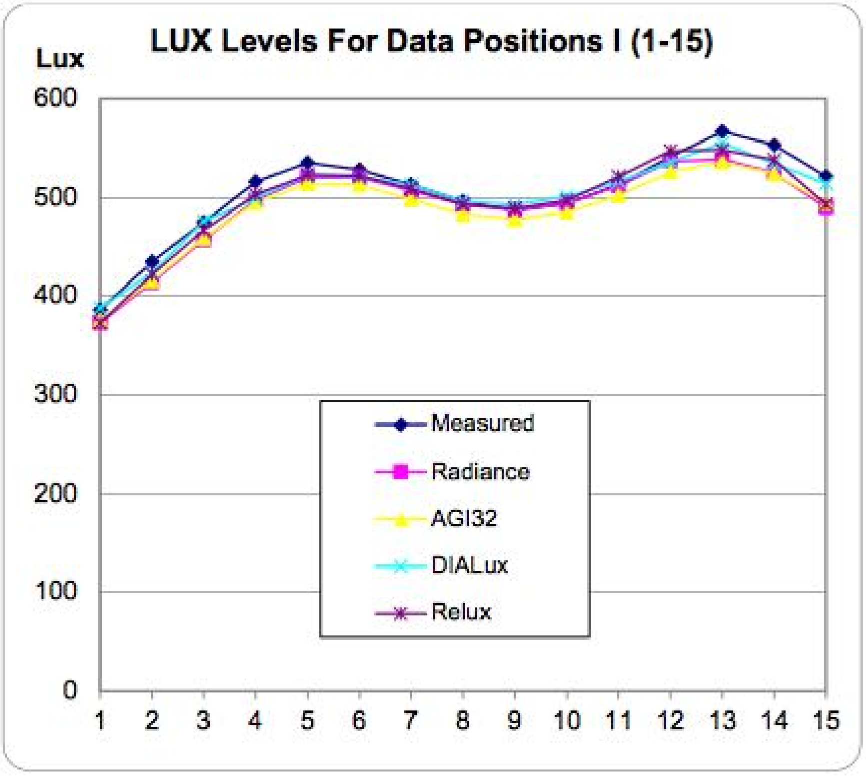

Figure 7-5 Comparison of measured and simulated illuminance data for 4 lighting simulation packages

Results show that, in all of the above occasions, all software remain very close to measured lux values. Differences in results range between 1% and 6%. A closer examination of all data points throughout the grid revealed that the average difference between measured and simulated data was 2.7% for RADIANCE, 2.7% for Relux, 5.5% for DIALux and 4.8% for AGI32. As Relux uses the same calculation code as RADIANCE, it was expected that the two software would provide similar results.

In building regulations and guidance, the average light levels in a room are typically considered. Thus, the average lux levels obtained in all occasions were also compared, together with the maximum and minimum lux levels, as shown in Figure 7-6. Results agree with observations made on individual lux level sample points, where RADIANCE and Relux are closer to measured values than DIALux and AGI32.

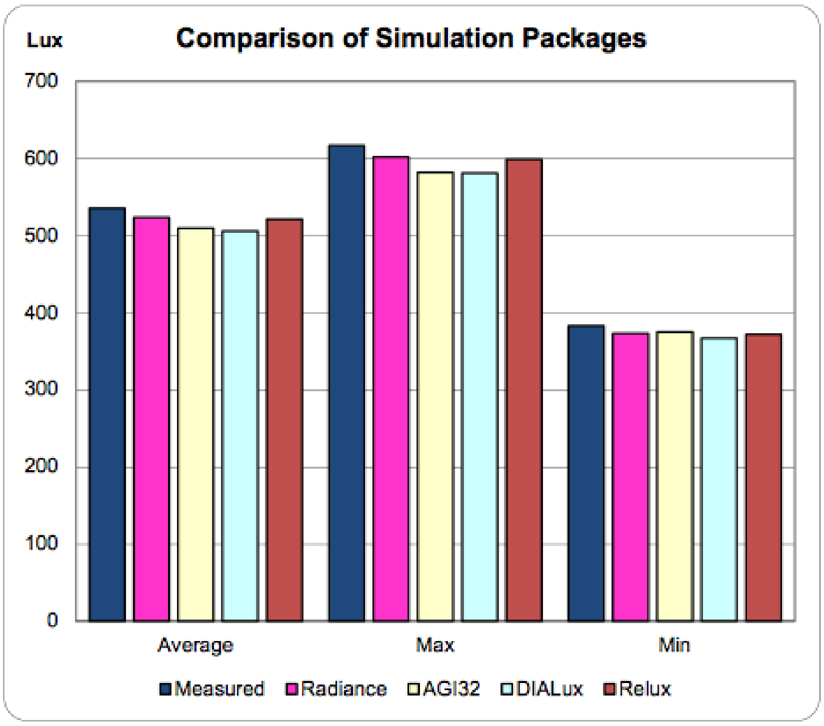

Figure 7-6 Comparison of measured and simulated in terms of overall average, maximum data value and minimum data value

The results obtained show close agreement between all simulation software and measured data. This was to be expected as all software are extensively used in industry and academia for their accuracy, and also because accurate photometric data existed for the fluorescent luminaire from the manufacturer.

LEDs are light sources that emit light just as other light sources do. Thus, there is no difference in the way that they are considered by light simulation software. Once photometric specifications are provided, their light output in a room can be predicted just as with any other light sources.

Photometric specifications are typically provided as photometric data sheets from manufacturers, as shown in Figure 7-7. In some cases, IES data files are provided too, but because their light output is usually symmetrical, it is relatively easy to compile an IES file within software like ECOTECT (Figure 7-8) or other similar software.

Figure 7-7 shows the distribution of the light of the designed lighting product. The ‘CD: 0 point’ is the point of the light output emission source of the luminaire, and, as it is shown, the light beam is quite narrow, which is typical in luminaires that use LEDs as a light source. Therefore, simulating the light output of an individual LED is not different than simulating the light output in a room from a whole luminaire when photometric specifications are available.

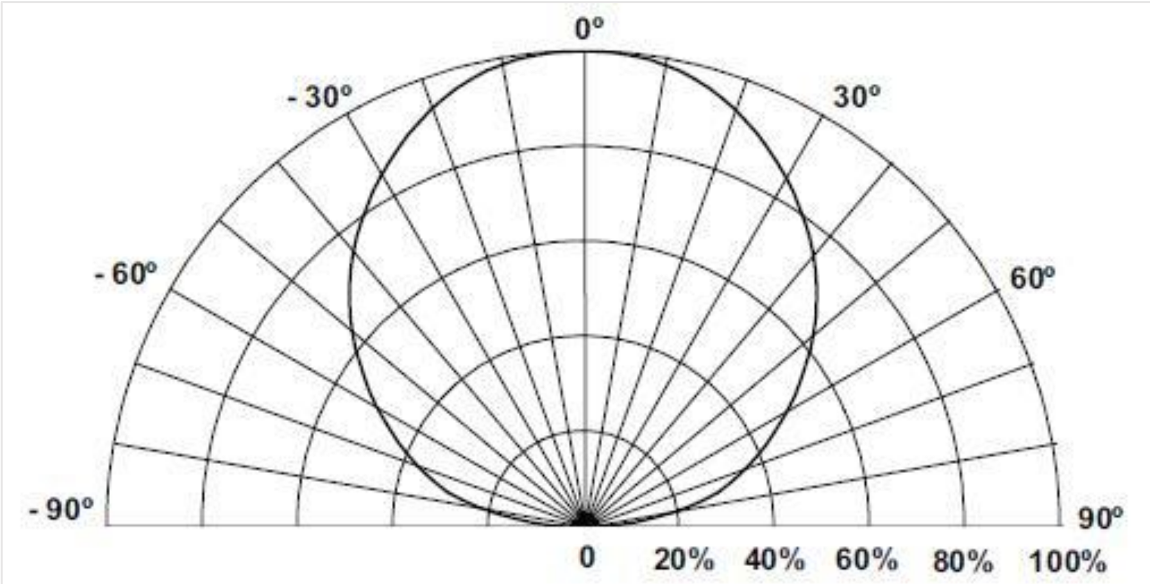

Figure 7-7 Polar radiation pattern for the designed lighting product

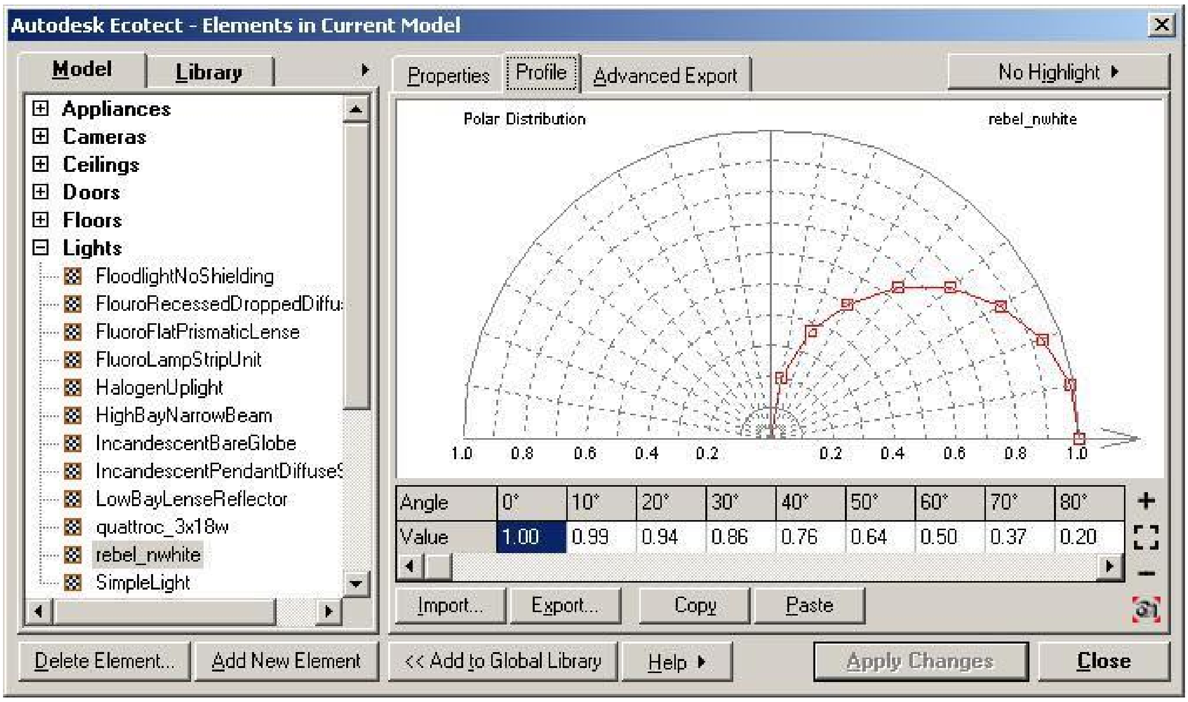

Figure 7-8 Photometric specification of light output profile in ECOTECT

One of the main differences as explained in the above, is that the light emitted by a single LED is very directional (along the centre axis of the LED), with little light emitted sideways, and is not enough to illuminate even a small room. This is very different from the case of an incandescent bulb or a fluorescent tube. As in the case of other light sources, photometric specifications are needed in order to simulate the light distribution in a room from an LED luminaire that houses many LEDs. Again, this is provided by manufacturers or laboratories in the form of a specification sheet or, most commonly, as an IES data file. The design of an LED luminaire though, containing many LEDs, entails quite a different process compared to other light sources. More specifically, in the case of fluorescent ceiling tile luminaires where two to four fluorescent tubes are typically used, it can be a process of placing the light sources in the luminaire housing and then moving them around manually until the desired light output is achieved by taking regular measurements throughout the process.

With LEDs, this is not possible as every single LED needs to be already designed as part of a module (containing one or more LEDs) with an appropriate heat sink so that heat is quickly and efficiently removed before the LEDs start to fail. This poses significant limitations in terms of adopting a manual method for constructing an LED luminaire and then measuring the light output to devise the IES data file. Hence, simulations are very commonly used by manufacturers when designing LED luminaires. Based on the analysis presented in this section, the designed lamp has successfully passed the lighting quality tests.

Chapter 8: Environmental Life Cycle Assessment of the LED Lighting Product

8.1 Introduction

LCA is best practiced as an iterative process, where the findings at each stage influence changes and improvements in the others to arrive at a study design that is of adequate quality to meet the defined goals. The principles, framework, requirements and guidelines to perform an LCA are described by the international standards ISO 14040 series (ISO, 2006a).

This chapter offers the LCA methodology and the scope of the study (section 8.2), the inventory data used and the assumptions (section 8.3 - 8.5), the LCIA results of the ONA LED lighting product (section 8.6), and conclusions and recommendation (section 8.7 - 8.8).

8.2 Goal and scope

8.2.1 Function and Functional Unit

The function of ONA lighting products is to provide efficient lighting service in a domestic environment. The functional unit quantifies the performance of a product system and is used as a reference unit for which the life cycle assessment study is performed, and the results are presented. It is therefore critical that this parameter is clearly defined and measurable.

The function of a luminaire is to produce a specific quantity and quality of light for a period of time. The quantity of light is measured with the luminous flux (lm) emitted by the luminaire, and the quality of light is mainly measured with the correlated colour temperature (CCT) and the colour rendering index (CRI). Therefore, the functional unit used in this LCA is considered as the production of 948 lm of light (quantity of light) of CCT=4000 K, and CRI=65 (quality of light) for 40,000 hours. Therefore, the function unit in this study is defined below:

Functional unit = 1 luminaire providing lighting service 948 Lumens per hour + 40,000 working hours

8.2.2 Product General Description

The ONA luminaire is a table lamp (see Figure 5-5.) and its' technique specification is listed in Table 8-1.

Table 8-1 The technical specification of the table lamp

Item	Amount
LED useful lifetime	40,000 hours
Energy consumption (luminaire)	6.7 Watts
Luminous flux (Luminaire)	102.5 Lm
Luminaire efficacy	15.29 Lm/Watts
Light source efficacy	56.66 Lm/Watts
Luminous flux (Light source)	340 Lm
CRI (light source)	65
CCT (light source)	4000 °K
Beam angle - vertical spread (luminaire)	102.1°
Beam angle- horizontal spread (luminaire)	96.3°

8.2.3 System boundaries

The setting of system boundaries identifies the stages, processes and flows considered in the LCA and should include:

- All activities relevant to achieve the present LCA study objectives and therefore necessary to carry out the studied function; and
- All the processes and flows that significantly contribute to the potential environmental impacts.

This section describes the life cycle stages of the studied systems and determines which processes and flows are included in the LCA, i.e., what is considered to be in the system and is therefore analysed, and what is outside the system boundaries and therefore not included in the assessment.

The boundaries of this assessment comprise cradle-to-grave luminaire's life cycle processes. The processes related with the packaging (i.e., manufacturing, transport, use and end of life of packaging) have been excluded. Thus, the product life cycle stages included are: Extraction of materials, manufacturing (assembly), transportation, use and End of Life (EoL) of the luminaire. Below it can be seen a diagram (Figure 8-1) of the life cycle stages included in the assessment of the luminaire.

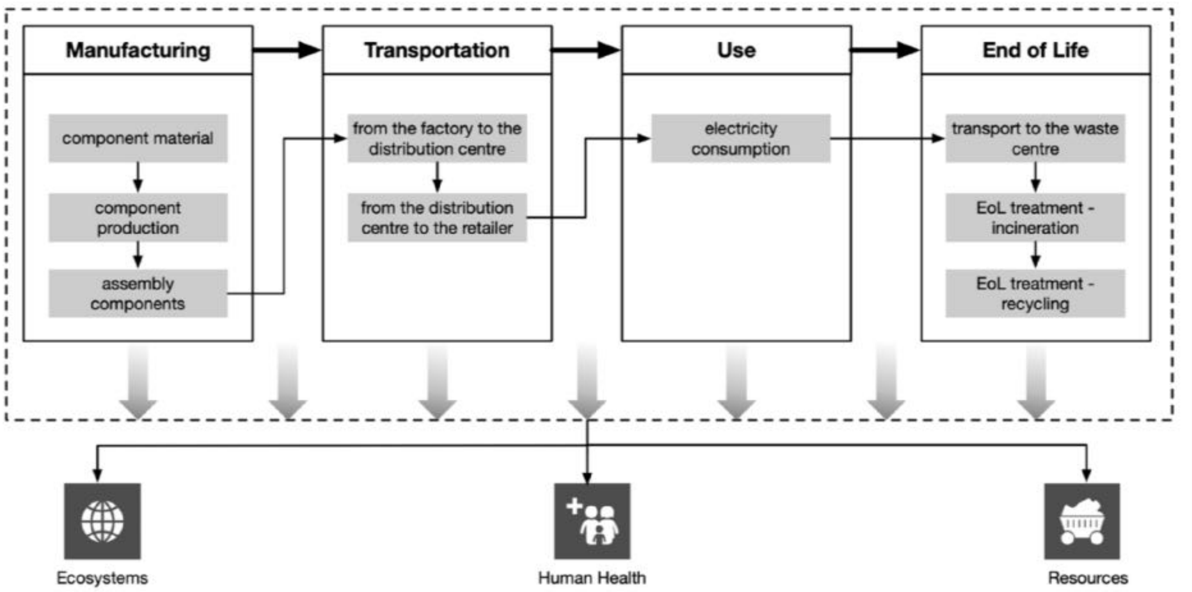

Figure 8-1 A schematic system for the luminaire life cycles

8.3 Life cycle impact assessment method

The life cycle impact assessment (LCIA) provides the basis for analysing the potential contributions of resource extractions and emissions in an LCI to a number of potential impacts. The impacts are calculated using characterization factors recommended in internationally recognized impact assessment methods.

According to ISO 14044 (ISO, 2006a), LCI flows of materials, energy and emissions into and out of each product system are classified into impact categories by the type of impact their use or release has on the environment. Then, they are characterized into their contribution to an indicator representing the impact category. The category indicator can be located at any intermediate position between the life cycle inventory results and the resulting damage (where the environmental effect occurs) in the cause-and-effect chain. The damage represents changes in environmental quality and a category indicator is a quantifiable representation of this change.

The ReCiPe method (Goedkoop *et al.*, 2009) is adapted in this study. The ReCiPe framework links all types of life cycle inventory results via several midpoint categories to three endpoints (damage oriented) categories (human health, ecosystems, resources). ReCiPe method was developed in 2008 by RIVM National Institute for Public Health and the Environment, CML, PRé Consultants and the Radboud University Nijmegen on behalf of the Dutch Ministry of Infrastructure and the Environment (RIVM, 2018).

The detailed life cycle assessment focuses on the three ReCiPe end-point indicators (Table 8-2) over the entire life cycle of the processes.

Table 8-2 ReCiPe endpoint indicators description (Goedkoop et al., 2009)

Endpoint Indicator	Endpoint Indicator Description	Impact Category
Human Health	This indicator measures the potential impact on human health caused by emissions associated with a product, process or organization. It takes into account human toxicity, accounting for both mortality (years of life lost due to premature death) and morbidity (rate of incidence of a disease). The impact metric is expressed in DALY ("disability-adjusted life years").	• Climate change Human Health • Ozone depletion • Ionising radiation • Photochemical oxidant formation • Human toxicity • Particulate matter formation
Ecosystems	Ecosystem quality can be described in terms of energy, matter and information flow. In the ReCiPe model the information flow at the species level is used. This means accepting the assumption that the diversity of species adequately represents the quality of ecosystems. This model gives the results as the potentially disappeared fraction of species (PDF) per unit area (m 2 or m 3) over a specified time period (yr).	• Agricultural land occupation • Climate change Ecosystems • Freshwater ecotoxicity • Freshwater eutrophication • Marine ecotoxicity • Natural land transformation • Terrestrial acidification • Terrestrial ecotoxicity • Urban land occupation
Resources	Resource depletion is modelled using the geological distribution of mineral and fossil resources and assesses how the use of these resources causes marginal changes in the efforts to extract future resources. The model is based on the marginal increase in costs due to the extraction of a resource. In terms of minerals, the effect of extraction is that the average grade of the ore declines, while for fossil resources, the effect is that not only conventional fossil fuels but also less conventional fuels need to be exploited, as the conventional fossil fuels cannot cope with the increasing demand. The	• Metal depletion • Fossil fuel depletion

	marginal cost increase is the factor that represents the increase of the cost of a commodity r ($/kg), due to an extraction or yield (kg) of the resource r. The unit of the marginal cost increase is dollars per kilogramme squared ($/kg 2).	

8.4 Calculation tool

The LCA software, SimaPro was used as the calculation tool, for conducting the life cycle assessment for this study. The ecoinvent 3.5 database was used for the life cycle inventory and the ReCiPe Endpoint (Heirarchist) method was chosen as the life cycle impact assessment method.

8.5 Life cycle inventory data

This section presents the main data and assumptions related to product different life stages, together with the choices of sensitivity analysis of key parameters.

Key material and process data are provided in section 8.5.1 that includes product main components production input, energy input, used as foreground data input of LCA model. Main assumptions and hypothesis are presented in section 8.5.2 that is used as data to compute foreground data input for LCA model as well as data input to build specific inventories. Choices of sensitivity analysis of key parameters is given in section 8.5.3.

8.5.1 Key Data for Materials and Processes

A Life Cycle Inventory is a compilation table of all energy and raw materials inputs and waste/emissions outputs associated with a product system. It is calculated by summing all LCI's of the relevant processes throughout the identified product system. The key parameters of the luminaire are presented in Table 8-3.

Table 8-3 Key parameters for the materials

Flow	Amount	unit	source
base	872	g	measured
Cable (including socket)	94	g	measured
lamp frame	28	g	measured
main frame	2836	g	measured
plug	9	g	measured
shade frame	344	g	measured
shade screen	104	g	measured
switch	8	g	measured
aluminium external case	10	g	measured
capacitor	4	g	measured
heat sink plate	14	g	measured
inductors	1	g	measured
joint-ring	1	g	measured
LED	1	g	measured
LED metal support	14	g	measured
LED power supply	3	g	measured
light diffuser	11	g	measured
metal thread	12	g	measured
plastic internal structure	18	g	measured
Printed Circuit Board (PCB)	5	g	measured
resistor	0.6	g	measured
screws	1	g	measured
Total	4390.6	g	measured

Key property and parameters of main processes of the luminaire system is given in Table 8-4 below.

Table 8-4 Key parameters of the processes

Process	Amount	Unit	Source
transport, freight, lorry 3.5 – 7.5 metric ton, EURO6	4.3906*189	Kg*km	ecoinvent
transport, freight, lorry, lorry >32 metric ton, EURO6	4.3906*1874	Kg*km	ecoinvent
Transportation distance (international)	1874	km	ecoinvent
Transportation distance (national)	189	km	ecoinvent
Use (default scenario)	6.7*40,000	Wh	ecoinvent
End of Life - incineration	2.63	kg	ecoinvent
End of Life – recycling	1.75	kg	ecoinvent

8.5.2 Data assumptions

The power cable and socket production have been assessed by selecting an average generic cable (from a typical computer desktop cable) available in ecoinvent databases.

Some plastic-based materials of components: switch (casing), LED bulb (joint ring, internal structure and light diffuser) and LED bulb holder, could not be identified by the authors and suppliers. In one case (internal structure of LED lamp) it could be identified, but the material (PBT) could not be found in the analysis software databases. Due to this data gap, assumptions based on closer material available selected. It was assumed that the plastic used in the switch was transparent polycarbonate (which is sometimes used in transparent casings' switches), and that the material used for the LED bulb plastic internal structure was PET, because is close related (in terms of composition) with PBT (real material of the part). PET was selected for the LED lamp diffuser, and for the joint ring, and Polycarbonate was selected for the LED bulb holder.

8.6 Life cycle impact assessment results

This section presents first the LCIA results for default and sensitivity scenarios. The goal is to identify and understand the most influencing stages or parameters to overall comparative LCA results.

8.6.1 Default scenario analysis

The parameters, methodological choices and assumptions used when modelling the product systems present a certain degree of uncertainty and variability. It is important to evaluate whether the choice of parameters, methods, and assumptions significantly influences the study's conclusions and to what extent the findings are dependent upon certain sets of conditions. Following the ISO 14044 standard (ISO, 2006a), sensitivity analyses are used to study the influence of the uncertainty and variability of modelling assumptions and data on the results and conclusions, thereby evaluating their robustness and reliability. Sensitivity analyses help in the interpretation phase to understand the uncertainty of results and identify limitations.

The End of Life scenario assumed the luminaire was disposal in household bins, following the 'municipal waste' treatment path. This is not an optimistic scenario, and if consumers dispose the luminaires in collection points for recycling, the environmental impact would be much lower.

The input and output flow of the default scenario is and described as follows:

- S1: the luminaire is used for 40,000 hours, distributed from Spain to the Netherlands, and disposed in municipal waste (60%) and recycling (40%).

8.6.1.1 Overall results

In this section it is highlighted the total environmental impact of the ONA luminaire, the differences of the various product's life cycle stages and the possible drivers for the various impact assessment indicators.

Figure 8-2 shows the impacts of the functional unit's life cycle, based on the input given from the default scenario. Due to the multi-indicator approach, results in the chart are presented in a relative way, normalized to the highest impact of each environmental impact categories among four life cycle stages; however absolute value and also relative value in percentage are available in Table 8-5 for transparency.

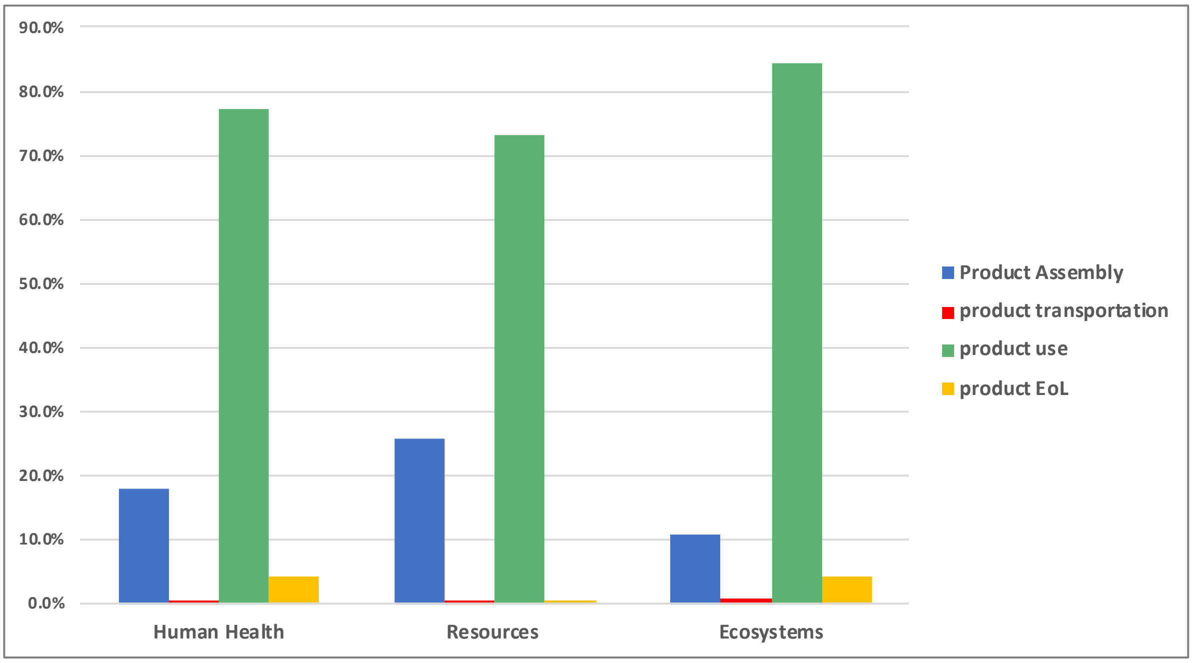

Figure 8-2 Life cycle impact results for the functional unit with the default scenario

Overall, it appears that the functional unit has higher impacts in the product use and assembly (manufacturing) stage compared to the other stages (Figure 8-2). Additionally, human health, resources, ecosystems are dominated by product use and product assembly (Figure 8-3).

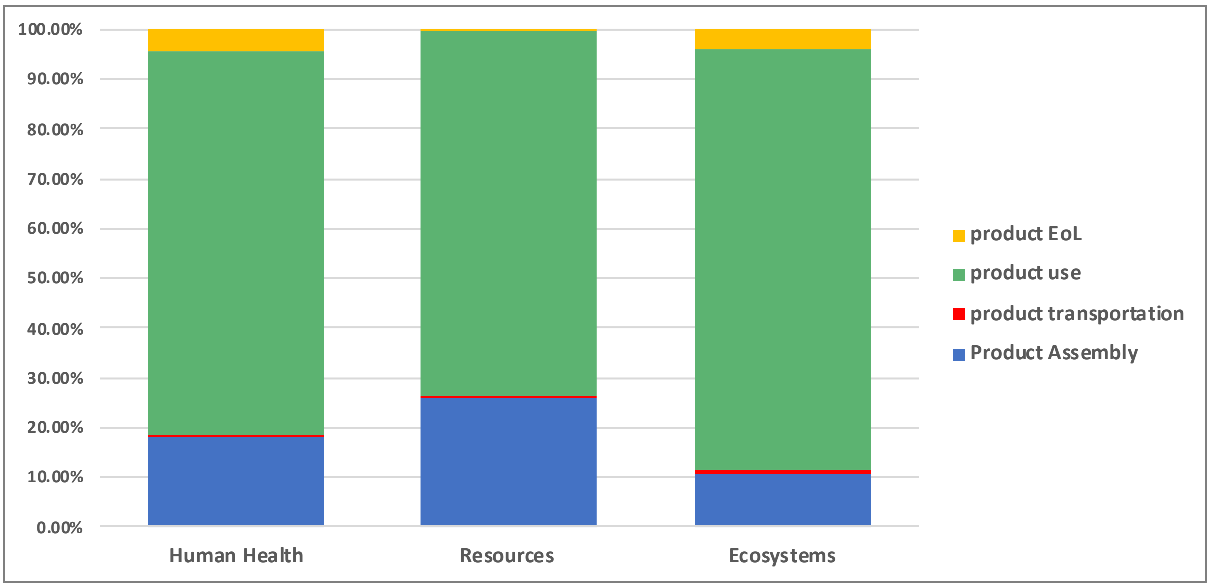

Figure 8-3 Environmental impact (endpoint) per impact category of the luminaire the default scenario

For human health and ecosystems impact, it shows more than 70% of impact come from product use, the rest 30% are associated with product assembly. These values might change depending on the functional unit's life span. In the default scenario, it's assumed to be 40,000 hours.

Table 8-5 Life cycle impact results of product stages under default scenario

Scenario	Product Life Stage	Human Health	Resources	Ecosystems
Default	Product Assembly	7.39E-05 (DALY)	3.00243 ($)	1.93E-07 (species.yr)
Default	product transportation	2.28E-06 (DALY)	0.07365 ($)	1.18E-08 (species.yr)
Default	product use	0.00032 (DALY)	8.53885 ($)	1.52E-06 (species.yr)
Default	product EoL	1.78E-05 (DALY)	0.03863 ($)	7.43E-08 (species.yr)
Percentage normalized to the highest value per impact category				
Default	Product Assembly	18.00%	25.76%	10.74%
Default	product transportation	0.56%	0.63%	0.66%
Default	product use	77.11%	73.27%	84.47%
Default	product EoL	4.34%	0.33%	4.14%

8.6.1.2 Detailed results- contribution analysis

Figure 8-4 presents the detailed contributions of the different processes to various environmental impact categories (endpoint level) of the luminaire's life cycles. Overall, the luminaire's life cycle has significant impacts on ecosystem (freshwater ecotoxicity, terrestrial ecotoxicity, marine ecotoxicity). Also, product use and product assembly cause overall highest environmental impacts, except freshwater ecotoxicity, terrestrial ecotoxicity, marine ecotoxicity.

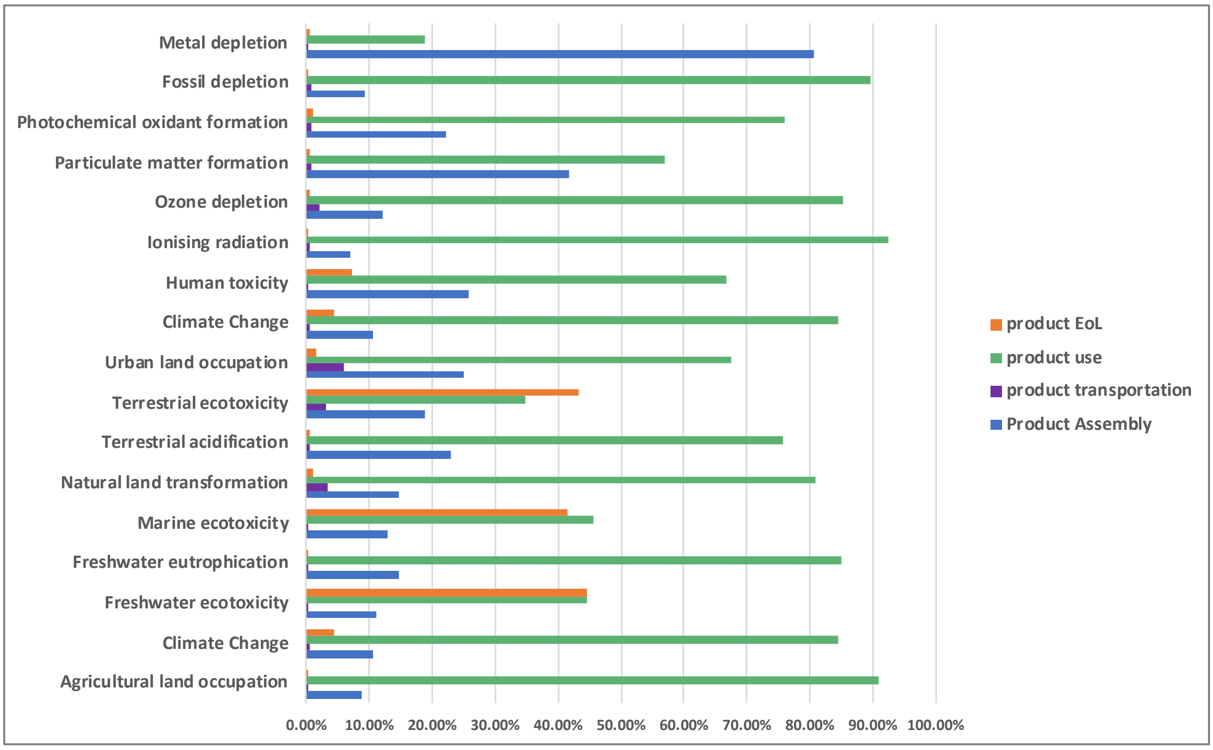

Figure 8-4 Contribution analysis of the functional unit's processes under default scenario

For human health impact, 77.1% of impact come from air pollutants emitted from electricity generation processes and 10.9% from the main frame (steel) manufacturing. Notable pollutants are sulfur dioxide, nitrogen oxides, PM 2.5.

For Ecosystem impact, it is again dominated by product use stage. The results show majority of impact come from electricity generation and steel manufacturing. Main pollutants are nitrogen oxides, aluminum, sulfur dioxide emitted to air.

For Resources, electricity again dominates the total impact. Similar to ecosystem quality, majority impact come from electricity generation and steel manufacturing. Main elementary flow contributors are Coal, hard; Oil, crude; Gas, natural/m3; Uranium; Coal, brown.

8.6.2 Sensitivity Analysis

To consider the three typical periods observed in electronic products, three useful life scenarios are assumed: 1000 hours, 20 ,000 hours and 40,000 hours. The scenario of 1000 hours assume an early failure due to manufacturing faults, the scenario of 20,000 hours assume a random failure or the substitution of the luminaire due to a technology/aesthetics upgrade, and the scenario of 40,000 hours assume an 'ideal' useful life, based on the average useful life of LEDs provided by LED suppliers. It is an 'ideal' scenario because this figure is provided by the LED supplier based on long-term extrapolations of shorter temporal tests conducted in a laboratory under ideal controlled operating conditions.

Therefore, scenarios are constructed to model sensitivity of key parameters, as listed in below.

- √ S1: the luminaire is used for 40,000 hours, distributed from Spain to the Netherlands, and disposed in municipal waste (60%) and recycling (40%).
- √ Scenario 2: the luminaire is used for 40,000 hours, distributed from Spain to the Netherlands, and disposed in a municipal waste (80%), and recycling (20%).
- √ Scenario 3: the luminaire is used for 40,000 hours, distributed from Spain to the Netherlands, and disposed of in a municipal waste (20%), and recycling (80%).
- √ Scenario 4: the luminaire is used for 20,000 hours, distributed from Spain to the Netherlands, and disposed in municipal waste (60%) and recycling (40%).
- √ Scenario 5: the luminaire is used for 20,000 hours, distributed from Spain to the Netherlands, and disposed in a municipal waste (80%), and recycling (20%).
- √ Scenario 6: the luminaire is used for 20,000 hours, distributed from Spain to the Netherlands, and disposed of in a municipal waste (20%), and recycling (80%).
- √ Scenario 7: the luminaire is used for 1500 hours, distributed from Spain to the Netherlands, and disposed in municipal waste (60%) and recycling (40%).
- √ Scenario 8: the luminaire is used for 1500 hours, distributed from Spain to the Netherlands, and disposed in a municipal waste (80%), and recycling (20%).
- √ Scenario 9: the luminaire is used for 1500 hours, distributed from Spain to the Netherlands, and disposed of in a municipal waste (20%), and recycling (80%).

The following sensitivity tests are conducted to understand the magnitude of importance of their influence on total LCA results.

Table 8-6 shows the overview of sensitivity results. The obtained results have been also reported in relative terms in Figure 8-5.

Table 8-6 Sensitivity results, Impact analysis total results for scenarios

Scenarios	Ecosystems (species.yr)	Human Health (DALY)	Resources ($)
S1 (default)	1.79E-06	4.11E-04	1.17E+01
S2	1.81E-06	4.16E-04	1.16E+01
S3	1.75E-06	4.01E-04	1.17E+01
S4	2.07E-06	5.05E-04	1.48E+01
S5	2.11E-06	5.15E-04	1.48E+01
S6	1.99E-06	4.85E-04	1.48E+01
S7	1.34E-05	4.24E-03	1.37E+02
S8	1.42E-05	4.43E-03	1.37E+02
S9	1.18E-05	3.84E-03	1.38E+02

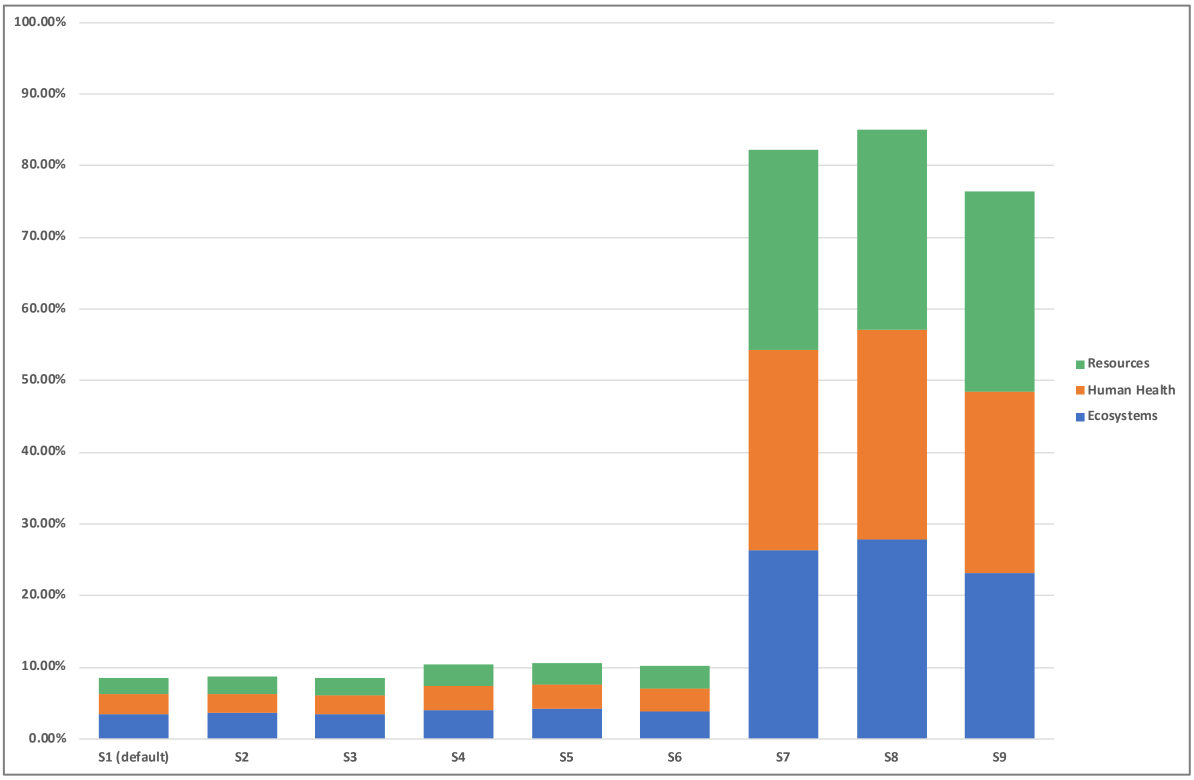

Figure 8-5 Relative impacts (total) among scenarios

Sensitivity results overall show the same luminaire has a longer life span (use stage) has lowest impacts (Figure 8-5, Table 8-6). This conclusion is consistent with the analysis results in default scenario that the impact from the electricity power generation process is the key factor affecting the impacts, which proves that the life cycle impact analysis in the default scenario is correct.

S1, S2 and S3 have the lowest impact amongst all the scenarios because the luminaire has the longest useful life (40,000 hours). The impact in all categories occurs mainly during the use stage, followed by the manufacturing stage.

S7, S8, S9 (S1: 1000 hours – domestic bin) has the highest environmental impact, followed by Scenario 2 (S2: 1000 hours recycling). S7 and S8 has a lower impact than S9 because the luminaire is recycled at the end of life. The reason for the minimal difference in impact is because the end of life stage plays a minor role in the total impact of the luminaires.

8.7 Comparison of LCA analysis results

Except the evaluation on lighting quality of the designed lighting product, the environmental performance assessment is also required based on the requirements of the integrated approach. The comparison results (Figure 8-6 and Table 8-7) of the redesigned table lamp (product A) and bench mark product (product B) are presented in the following three end-point damage categories: Human Health (HH), Ecosystem Quality (EQ) and Resources (R).

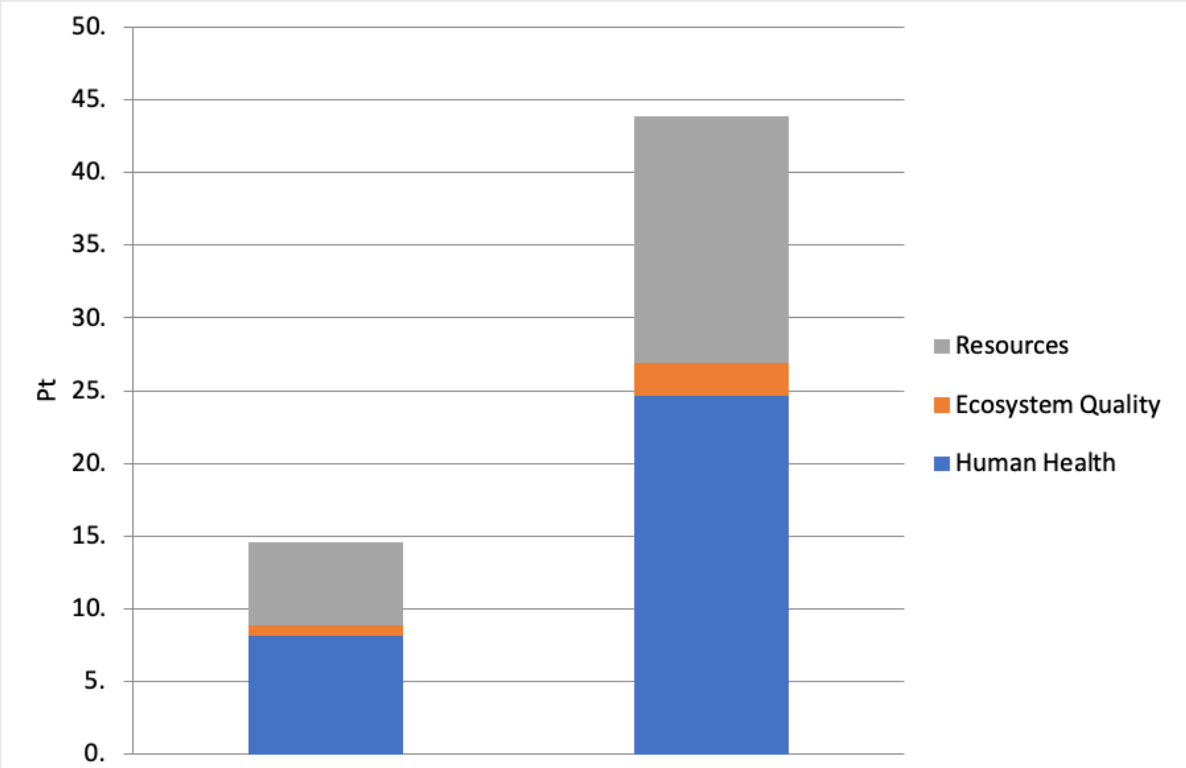

Figure 8-6 Results per damage category

Table 8-7 Results per damage category

Damage category	Unit	Designed lighting product (Product A)	Benchmark product (Product B)
Total	Pt	14.608934	43.883193
Human Health	Pt	8.1495463	24.665901
Ecosystem Quality	Pt	0.74406188	2.2643321
Resources	Pt	5.7153254	16.95296

Results show that the Benchmark product has much higher environmental impact than the redesigned light (43.88 vs. 14.60). The damage category with higher impact in both products is 'Human Health' (Redesigned light: 8.14 vs. Benchmark: 24.66), followed by 'resources' (Redesigned light: 5.71 vs. Benchmark: 16.95), and 'ecosystem quality' (Redesigned light: 0.74 vs. Benchmark: 2.26). In all damage categories the comparative product has higher values than the Redesigned light.

The results, Figure 8-7 and Table 8-8, of the redesigned LED lamp are presented in the following eleven impact categories: Fossil Fuels, Minerals, Land Use, Acidification/Eutrophication, Ecotoxicity, Ozone Layer, Radiation, Climate Change, Respiratory Inorganics, Respiratory Organics and Carcinogens.

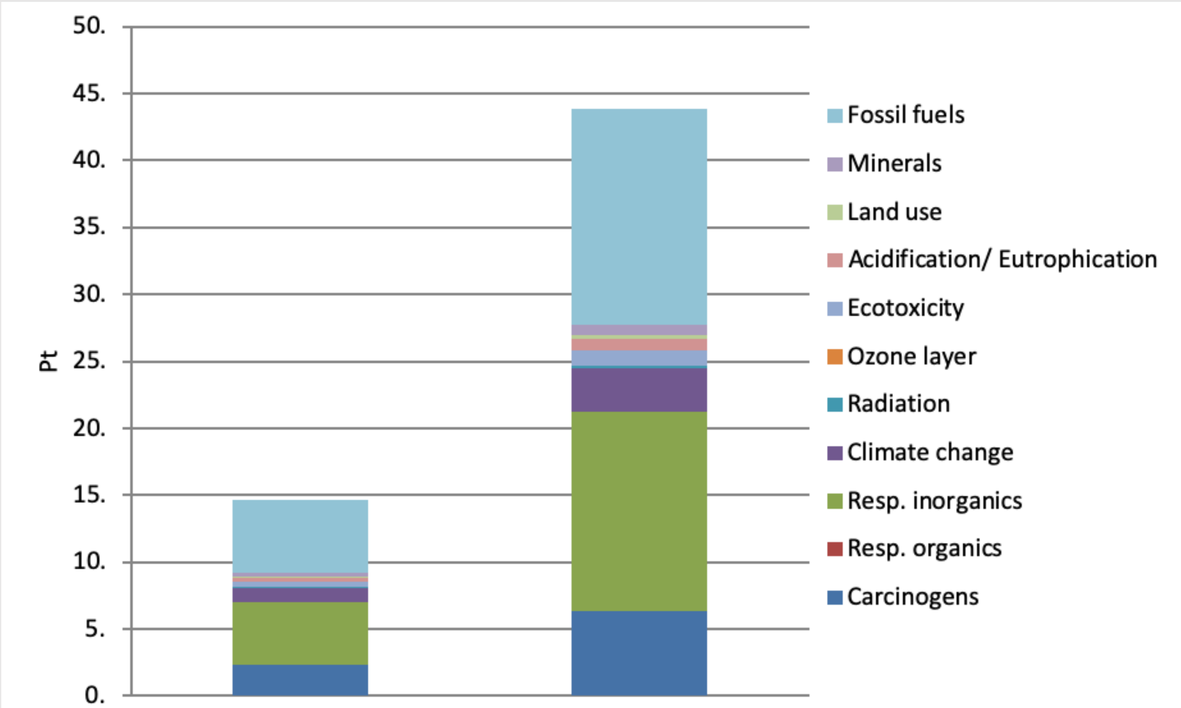

Figure 8-7 Results per impact category

Table 8-8 Results per impact category

Impact category	**Unit**	**Product A**	**Product B**
Total	Pt	14.608934	43.883193
Carcinogens	Pt	2.3647265	6.3496849
Resp. organics	Pt	0.002005205	0.004417073
Resp. inorganics	Pt	4.6684448	14.851242
Climate change	Pt	1.0569012	3.2767993
Radiation	Pt	0.057182945	0.18285652
Ozone layer	Pt	0.000285721	0.000901272
Ecotoxicity	Pt	0.3950197	1.1628713
Acidification/ Eutrophication	Pt	0.26057544	0.83088608
Land use	Pt	0.088466741	0.27057473
Minerals	Pt	0.36076051	0.81276345
Fossil fuels	Pt	5.3545648	16.140197

When look at the results per impact category, we can see that the impact category with higher value for both products is 'fossil fuels' (Redesigned light: 5.35 vs. Benchmark: 16.14).

This is due to the high demand of energy (and electricity production) to make the products function during their useful lifespan. The second impact category with higher impact is 'respiratory inorganics' (Redesigned light: 4.66 vs. Benchmark: 14.85), followed by: 'carcinogens' (Redesigned light: 2.34 vs. Benchmark: 6.34), 'climate change' (Redesigned light: 1.05 vs. Benchmark: 3.27), 'ecotoxicity' (Redesigned light: 0.39 vs. Benchmark: 1.16), 'Minerals' (Redesigned light: 0.36 vs. Benchmark: 0.81), 'acidification/eutrophication' (Redesigned light: 0.26 vs. Benchmark: 0.83), 'Land use' (Redesigned light: 0.088 vs. Benchmark: 0.27), 'radiation' (Redesigned light: 0.057 vs. Benchmark: 0.18), 'respiratory organics' (Redesigned light: 0.002 vs. Benchmark: 0.00441) and 'ozone layer' (Redesigned light: 0.00028 vs. Benchmark: 0.00090).

8.8 Conclusions

Overall, it shows that major impacts come from the electricity power consumption process in product use stage, and steel production process in the product assembly stage. Also, the luminaire's useful life span is the key factor affecting the impacts. Among all of the luminaire's components, the main frame contributes the most impacts (10.9% for Human Health, 7.4% for Ecosystems, 20.5% for Resources), which could be considered by the product engineers to replace with other materials instead of steel. The disposal treatment doesn't have much effects for environmental impacts of the end of life luminaire with a longer life span (i.e. beyond 20,000 hours). Also, recycling the luminaire's components (e.g. frame, cable) can significantly reduce the resource impacts, which proves the necessity of offering an incentive scheme to encourage consumers to implement more recycling.

Chapter 9: Social Life Cycle Assessment for the LED Lighting Product

9.1 Introduction

Social sustainability is a wide concept, which covers several definitions and can be approached through different methodologies (Florman, Klingler-Vidra and Facada, 2016; Rafiaani *et al.*, 2018) list general and specific social impact assessment methodologies launched since 1997, as for example, Social Return on Investment (SROI) and Social Value Metrics. More specifically, Rafiaani et al. compare within bio-based economy the Social Impact Assessment (SIA), Socio-Economic Impact Assessment (SEIA) and Social Life Cycle Assessment (Rafiaani *et al.*, 2018). In order to evaluate the sustainability assessment of the domestic lighting products, social aspects are conducted from a Life Cycle Assessment point of view. Thus, standards ISO 14040/44 stablish S-LCA framework. Thus, S-LCA is a procedure for social impacts analysis within products' life cycle, which assesses social and socio-economic features of products, as well as, potential positive and negative impacts (Andrews, 2009). It has to be highlighted that existing social impact methodologies at product level foster flexibility due to relative immaturity and specific background requirements.

This chapter contains the results of the Social Life Cycle Impact Assessment of ONA domestic lighting product; using existing and new innovative methods of social impact analysis. These results represent a reference scenario for the future assessment of innovation solutions. Finally, a conclusion section is added including the main findings and recommendations for every product.

9.2 Methodology for the social life cycle assessment

SLCA presents some methodological particularities that are defined hereafter and which are amended to the demonstrators characteristics (UNEP/SETAC/LCI, 2009). The social impact assessment is made in a similar way than the environmental life cycle assessment, and in agreement with it since the initial stages for the analysis design and configuration are the same. The four main phases of a Life Cycle Assessment are related to each other as depicted in Figure 9-1 (ISO, 2006b).

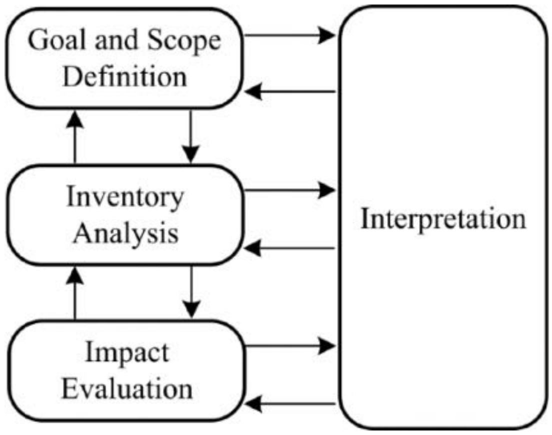

Figure 9-1 Principal phases of an LCA study

The first step defines the goal and scope of the analysis, starting by defining the functional unit of the assessment. In this case, the assessment is focused on products, and the functionality is given by one complete unit of product ready for consumption: 1 unit of table lamp (domestic lighting product). In this step, the scope of the analysis is also determined based on the goals of the study. The largest scope is a cradle-to-cradle analysis that comprises all life cycle stages, including material disposal and end of life of the products. Based on the defined scope, the inventory of inputs/outputs of each life cycle stage per functional unit is retrieved, either from own sources, or from appropriate databases. The impact evaluation for a SLCA consists in the aggregation of all social impacts weighed by the national and sectoral risk factors, and it is provided in comparable medium risk hours. Assessment of most impacting stages and activities may be done, as well as comparisons with possible scenario planning. Finally, the interpretation of the results allows to iterate the analysis among the previous steps.

On the other hand, in order to conduct a comprehensive and comparable social evaluation, SLCA approach is disaggregated by subcategories, which are socially relevant topics or aspects. These subcategories can be classified by impact category and stakeholder categories. Stakeholder category can be defined as a group of agents, which foreseeable have common interests in accordance with their relationship with the product system under study (Fontes *et al.*, 2014). Figure 9-2 describes relationships between the main stakeholders associated with business and products. Considering the lack of scientific or international accepted inventory classification models as concluded by (Hsu, Wang and Hu, 2013), this approach can become a solid foundation for subcategories structuration.

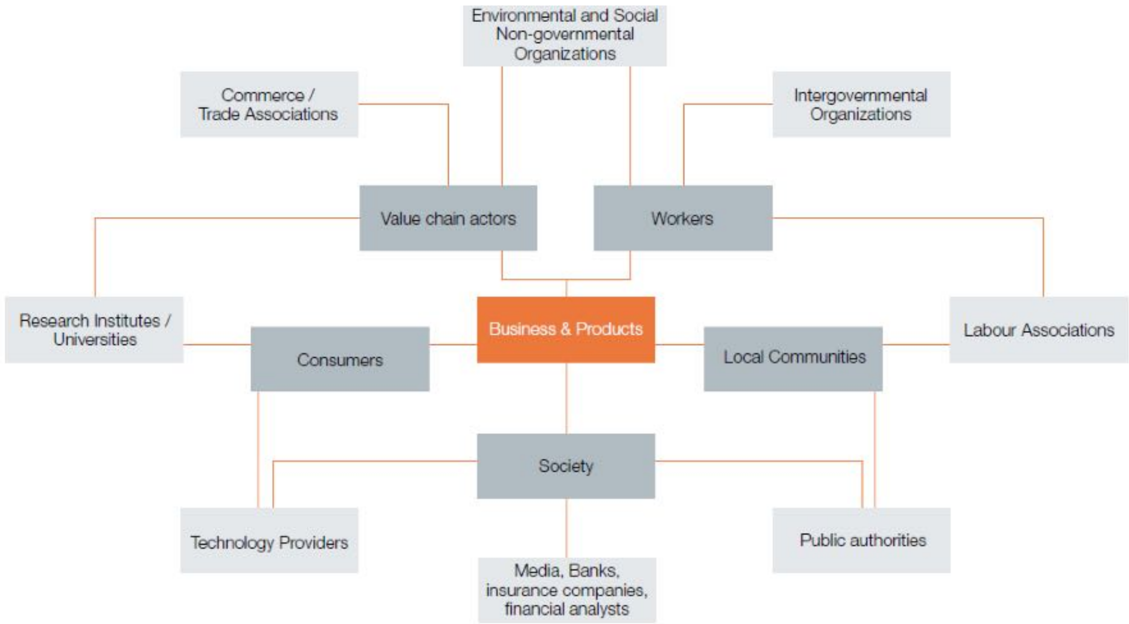

Figure 9-2 Relationship between stakeholders (UNEP/SETAC/LCI, 2009)

It is needed to highlight that unlike environmental and economic approaches, SLCA relies on indicators that may be: i) quantitative, ii) semi-quantitative and iii) qualitative. In fact, it is recommended a parallel work with both, quantitative and qualitative indicators, due to quantitative indicators may not cover social dimensions completely (Grießhammer *et al.*, 2006). It has to be noted that, consumers stakeholder category includes end-consumers and intermediate consumers within the supply chain and that, value chain actors do not consider consumers.

Thus, the methodology proposed for this SLCA implementation in this chapter is presented in Figure 9-3. It should be mentioned that this methodology was adapted from the systemic approach for social sustainability assessment proposed by (Rafiaani *et al.*, 2018)(Gimeno-Frontera *et al.*, 2018).

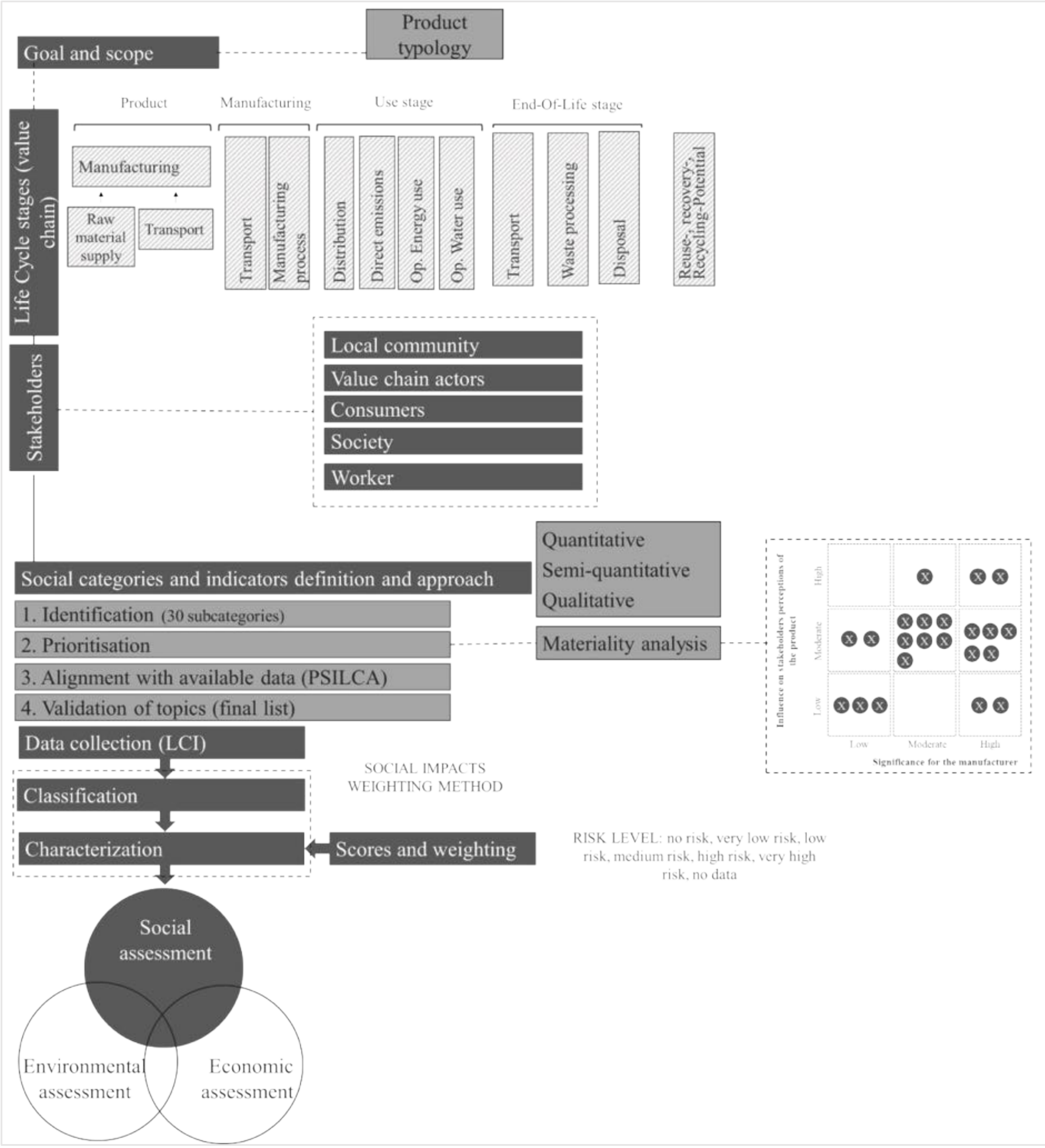

Figure 9-3 Overall methodology proposed for S-LCA implementation (UNEP 2020)

9.3 Social life cycle impact assessment

9.3.1 Social categories/subcategories and indicators definition

The social categories and indicators are based on the 'Guidelines for social life cycle assessment of products' (UNEP/SETAC/LCI, 2009) and 'The Methodological Sheets Guidelines for Subcategories in Social Life Cycle Assessment' (Benoît *et al.*, 2010), designed for the social life cycle assessment of products and services. They include 5 stakeholders typologies, and 23 social and socio-economic subcategories (topics).

There are not many complete databases about social aspects of products and services, that include most of the UNEP/SETAC categories and indicators. Several requirements are elicited in the search of the most suitable social impact database. Among others, a database should meet the following minimum requirements:

- Commercially available.
- World-wide global coverage of social aspects.
- Stakeholder, impact categories and subcategories, and indicators in line with widely recognised official methodologies like the UNEP's Life Cycle Initiative
- Compatible with commonly used aggregation and calculation tools like openLCA and SimaPro.
- Information is transparent, comprehensive and updated regularly.
- Validated and backed by well-known experts and institutions.

From the list of requirements above, the best positioned in the market is PSILCA (Ciroth and Eisfeldt, 2017). PSILCA stands for 'Product Social Impact Life Cycle Assessment' and it is a database developed by GreenDelta. In order to provide insights into global supply chains, PSILCA uses a multi-regional input/output database, called Eora. Eora covers the entire world economy, on an industrial sector basis, comprising 189 countries and nearly 16,000 activity sectors distributed in Industries and commodities per country. Eora features raw data drawn from the UN's System of National Accounts, Eurostat, Comtrade database and many national agencies.

The reference year of the database is 2011. As an Input-Output database, Eora uses money flows to link processes. All process inputs are given in 2011’s US dollars, while impact outputs are calculated in equivalent medium-risk working hours. This system enables the linkage of heterogeneous processes, and the comparison of impact results. The list of social subcategories and social indicators in PSILCA are listed in Table 9-1.

Table 9-1 List of social subcategories in PSILCA and social indicators

Stakeholder	PSILCA Subcategory	Indicator
Workers	Child labour	Children in employment, male
		Children in employment, female
		Children in employment, total
	Forced labour	Goods produced by forced labour
		Frequency of forced labour
		Tier placement referring to trafficking in persons
	Fair salary	Living wage, per month
		Minimum wage, per month
		Sector average wage, per month
	Working time	Hours of work per employee, per day
		Hours of work per employee, per week
		Standard weekly hours
		Standard daily hours
	Discrimination	Occurrence of discrimination
		Women in the labour force
		Men in the labour force
		Gender wage gap
		Accident rate at workplace
		Fatal accidents at workplace
		Occupational risks
		DALYs due to indoor and outdoor air and water pollution
		Presence of sufficient safety measures
		Workers affected by natural disasters
	Social benefits, legal issues	Social security expenditures
		Evidence of violations of laws and employment regulations
	Workers´ rights	Freedom of association rights
		Trade union density as a % of paid employment total
		Right of Association
		Right of Collective bargaining
		Right to Strike
Value Chain Actors	Fair competition	Presence of anti-competitive behaviour or violation of anti-trust and monopoly legislation
		Presence of policies to prevent anti-competitive behaviour
	Corruption	Corruption index of country
		Evidence of an active involvement of the enterprises in corruption and bribery

Stakeholder	PSILCA Subcategory	Indicator
	Promoting social responsibility	Presence of codes of conduct that protect human rights of workers among suppliers
		Membership in an initiative that promotes social responsibility along the supply chain
	Supplier relationships	Interaction of the companies with suppliers
Society	Contribution to economic development	Economic situation of the country
		Contribution of the sector to economic development
		Public expenditure on education
		Illiteracy rate, male
		Youth illiteracy rate, male
		Illiteracy rate, female
		Youth illiteracy rate, female
		Illiteracy rate, total
		Youth illiteracy rate, total
	Health and safety	Health expenditure, Total
		Health expenditure, Public
		Health expenditure, Out of pocket
		Health expenditure, External resources
		Health expenditure out of the total GDP of the country
		Life expectancy at birth
	mitigation of conflicts	Risk of conflicts with regard to the sector
Local Community	Access to material resources	Level of industrial water use
		Level of industrial water use, out of total withdrawal
		Level of industrial water use, out of total actual renewable
		Extraction of material resources (other than industrial water)
		Extraction (total) of fossil fuels
		Extraction (total) of biomass
		Extraction (total) of ores
		Extraction (total) of biomass
		Extraction (total) of industrial & const. minerals
		Presence of certified environmental management systems
		Description of (potential) material resource conflicts
	Respect of indigenous rights	Presence of indigenous population
		Human rights issues faced by indigenous people
		(Company´s) respect of indigenous rights
	Safe and healthy living conditions	Pollution level of the country
		Contribution of the sector to environmental load
		Drinking water coverage
		Sanitation coverage
		Management effort to improve environmental performance
	Local employment	Unemployment rate in the country
		Work force hired locally
		Percentage of spending on locally based suppliers
	Migration	International migrant workers in the sector
		International Migrant Stock
		Net migration rate

Stakeholder	PSILCA Subcategory	Indicator
		Emigration rate
		Immigration rate
		Human rights issues faced by migrants
Consumers	Health and Safety	Violations of mandatory health and safety standards
		Presence of commissions/institutions to detect violations of standards and protect consumers
		Presence of management measures to assess consumer health and safety
	Transparency	Presence of business practices that are deceptive or unfair to consumers
		Presence of certifications or labels for the product/sites sector
		Presence of a law or norm regarding transparency (by country/sector)
	End of life responsibility	Strength of national legislation covering product disposal and recycling

PSILCA enables to use weighing factors to assess the level of risk of each indicator according to a risk scale moving from very high risk to very low risk, including a 'no risk' level. Assessment is made using normalised values by activity sector and country. Risk level allocation limits are also documented and can be tailored with specific national, sectoral or corporate data.

Since not all data sources are equally trustful, the data quality can also be evaluated according to several indicators in a 1-to-5 scale, as follows:

- Reliability of the sources
- Completeness conformance in terms of data representativeness for country-specific sector.
- Temporal conformance, in years of difference to the time period of the dataset.
- Geographical conformance at country or region level.
- Further technical conformance such as data from the same technology or sector, or different.

From the initial set of subcategories, an identification was done in order to select the more meaningful ones considering the sectors under study (Table 9-2), complying with the following criteria:

- **Geographical relevance**: applicability of the social impact within the European context for foreground processes in Spain and United Kingdom. To verify this criteria, National-, sector-, and company-specific data and comments for each subcategory in all five stakeholder categories were collected from industrial partners. National level indicator classified as 'not applicable' or omitted are considered as out of boundary in respect of the socioeconomic framework of the EU.

- **Data availability:** this criterion is not to get comparable results among heterogeneous products/process, but to guarantee that the methodology and the results' structure is equivalent for all parts involved. The information collected from ONA was checked to verify if data is available for each of the indicators in all the subcategories. A scale is used to classify how much information per indicator is indeed collectable and, thus, if the subcategory is feasible to be assessed.
- **Bibliography validation:** the last criterion verifies the pertinence given by S-LCA specialised literature over the last decade. Three main sources are consulted: i) the findings of (Jørgensen *et al.*, 2008), one of the most cited papers in the field, that include the review of 11 S-LCA studies until 2008, ii) the updated review done by (Siebert *et al.*, 2018) that comprises an extra 12 S-LCA papers; and iii) the most recent report on S-LCA done by the Joint Research Centre (JRC) in 2018 (Mancini, Eynard and Eisfeldt, 2018). The three sources sum a total of 24 cases that serve to identify the most relevant social indicators by their frequency of use.

Following the triple criteria of geographical relevance, data availability and bibliography validation, the identification of subcategories resulted in a final number of 13. Notice that the availability of information plays a key role in this exercise, whereas the bibliography validation serves more as an added value for the selection.

Table 9-2 Criteria for impact category and social indicator selection

Stakeholder	PSILCA Subcategory	Geographical relevance	Data availability	Bibliography validation	Result
		Yes/No	Out of 3	Out of 24	
Workers	Child labour	NO	0	8	NO
	Forced labour	NO	0	7	NO
	Fair salary	YES	3	20	YES
	Working time	YES	3	15	YES
	Discrimination	YES	2	20	YES
	Health and Safety	YES	2	20	YES
	Social benefits, legal issues	YES	1	5	NO
	Workers´ rights	YES	1.5	18	YES
Value Chain Actors	Fair competition	YES	3	0	YES
	Corruption	YES	1	1	NO
	Promoting social responsibility	YES	1.5	0	NO
	Supplier relationships	YES	3	0	YES
Society	Contribution to economic development	YES	2	13	YES
	Health and safety	YES	0.5	0	NO
	Prevention and mitigation of conflicts	YES	0	0	NO
Local Community	Access to material resources	YES	3	0	YES
	Respect of indigenous rights	NO	1	1	NO
	Safe and healthy living conditions	YES	1.5	6	YES
	Local employment	YES	3	5	YES
	Migration	YES	1	1	NO
Consumers	Health and Safety	YES	2	0	YES
	Transparency	YES	1	0	NO
	End of life responsibility	YES	3	0	YES

The identification of subcategories and indicators is then complemented with a materiality analysis that serves to assess the relevance of social topics according to partners' perspective, so a more effective focus may be set during the social impact assessment.

The materiality analysis allows a broader discussion regarding on social features significance, expectations and interest depending on, for example, regions and stakeholder category. Then, the process for social aspects selection, considering stakeholder inclusiveness, is based on: i) identification, ii) prioritization, iii) validation and iv) review according (Initiative, 2013; Fontes *et al.*, 2014). Hence, it is necessary to assess the relevance of social topics according to partners' perspective for the social impact assessment (Bellantuono, Pontrandolfo and Scozzi, 2016).

Given that the first step (identification) is already completed, the prioritization step is proposed to be done using a scoring system (High-Moderate-Low) for the significance of each of the identified subcategories for the activities within the value chain of the industrial partners' products, as well as, the influence of these matters on other stakeholders' perceptions of the product (workers, consumers, local community, society and value chain actors). It should be mentioned that validation and review will be done though the assessment of social impacts.

Table 9-3 show the results of the materiality matrix for the organic vegetables production, meat product and domestic lighting product, respectively, according to the feedback received from industrial partners.

According to ONA´s management, access to material resources (local community), Health and Safety (consumers), fair salary (workers) and contribution to economic development (society) are among the subcategories with a high significance for its business in relation with the product analysed. In addition, they have also identified the access to material resources (local community) and Health and Safety (consumers) as relevant subcategories with a high influence on stakeholders' perceptions of the product.

Table 9-3 Domestic lighting product materiality matrix

Stakeholder related to social topic	Subcategory	Manufacturing and Packaging		Transport		Use		End-of-life	
		Significance for your business	Influence on stakeholders' perceptions of the product	Significance for your business	Influence on stakeholders' perceptions of the product	Significance for your business	Influence on stakeholders' perceptions of the product	Significance for your business	Influence on stakeholders' perceptions of the product
Workers	Fair salary	High	Moderate	High	High	High	High	High	High
	Hours of Work	High	High	High	Moderate				
	Equal opportunities / Discrimination	High	High	High	High	High	High		
	Health and Safety	High	High	High	High	Moderate	Moderate		
	Freedom of Association and Collective Bargaining	Moderate	Moderate	High	Moderate	Moderate	Moderate		
Society	Contribution to economic development	High	High	High	High	High	High		
Local Community	Safe and healthy living conditions	High	Moderate	High	Moderate	Moderate	Moderate	Moderate	Moderate
	Access to material resources	High	High	High	High	High	High	High	High
	Local Employment	High	Moderate	High	High	High	High		
Consumers	End of life responsibility	High	High	Moderate	Moderate	Moderate	Moderate	High	High
	Health and Safety	High	High	High	High	High	High	High	High
Value chain actors	Fair competition	High	High	High	High	Low	Low	Low	Low
	Supplier relationships	High	High	High	Moderate	Low	Low	Low	Low

9.3.2 System description

The domestic lighting product selected as a reference product for the S-LCA is a LED Table Lamp produced by Ona, which is a design publisher of lighting projects and custom lamps. In addition to the design and quality of their products, they are also specialized in developing and manufacturing concepts and lighting products for different projects. They are located in Valencia, Spain. This lamp is characterized by simplicity in its form. According to the technical data of the product, the transparency of the tubular borosilicate screen makes the bulb visible, giving it a greater importance. Main elements are the white parchment screen, the metal lamp body and the LED bulb. Ona designs the product and sends to the providers for its manufacturing.

Functional unit

The selected functional unit is 1 unit of Table lamp with a reference useful life of 40,000 h. This is a standard luminaire which can provide ambient lighting. The technical specifications are presented by (Casamayor, Su and Ren, 2018) and are summarized in Table 9-4.

Table 9-4 Technical specifications of the luminaire

Characteristic	Unit	Value
Weight	g	4,390
Dimensions: x,y,z	cm	41x44x10
Luminous flux of luminaire	lm	102
Illuminance on luminaire's base	lx	882
Luminaire efficacy	lm/W	15
Power consumption of luminaire	W	6.7
Light output ratio	LOR	0.3
Correlated colour temperature (CCT)	K	4,000
Luminous flux of light source	lm	340
Light source efficacy	lm/W	56
Light source useful life	h	40,000

Flowchart

Figure 9-4 presents the different stages and main inputs considered for the assessment for the functional unit.

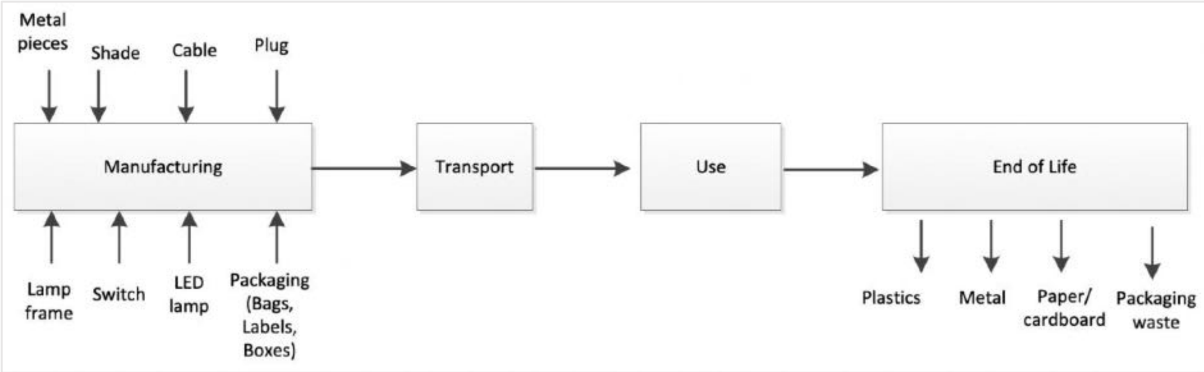

Figure 9-4 ONA's simplified process flowchart.

Boundaries of the system

The boundaries of the study comprise cradle to grave approach. Thus, the product life cycle stages considered includes the following stages:

- **Product:** extraction and production of materials.
- **Manufacture:** Manufacturing activities including packaging.
- **Transportation:** Main destination country: Spain.
- **Use:** The expected useful life of the product considered is 40,000 h. Maintenance activities are out of the scope of the analysis.
- **End of life:** end of life scenario considered for the product and packaging.

9.3.3 Life Cycle Inventory and quality data

A combination of data from own sources for the manufacturing processes and from PSILCA database for national and sectoral social data are used. All inputs are converted into currency per functional unit and life cycle stage and screened out to represent the value-added activities form material supply to manufacturing, distribution, consumption and end of life. The process under analysis is depicted in Figure 9-5.

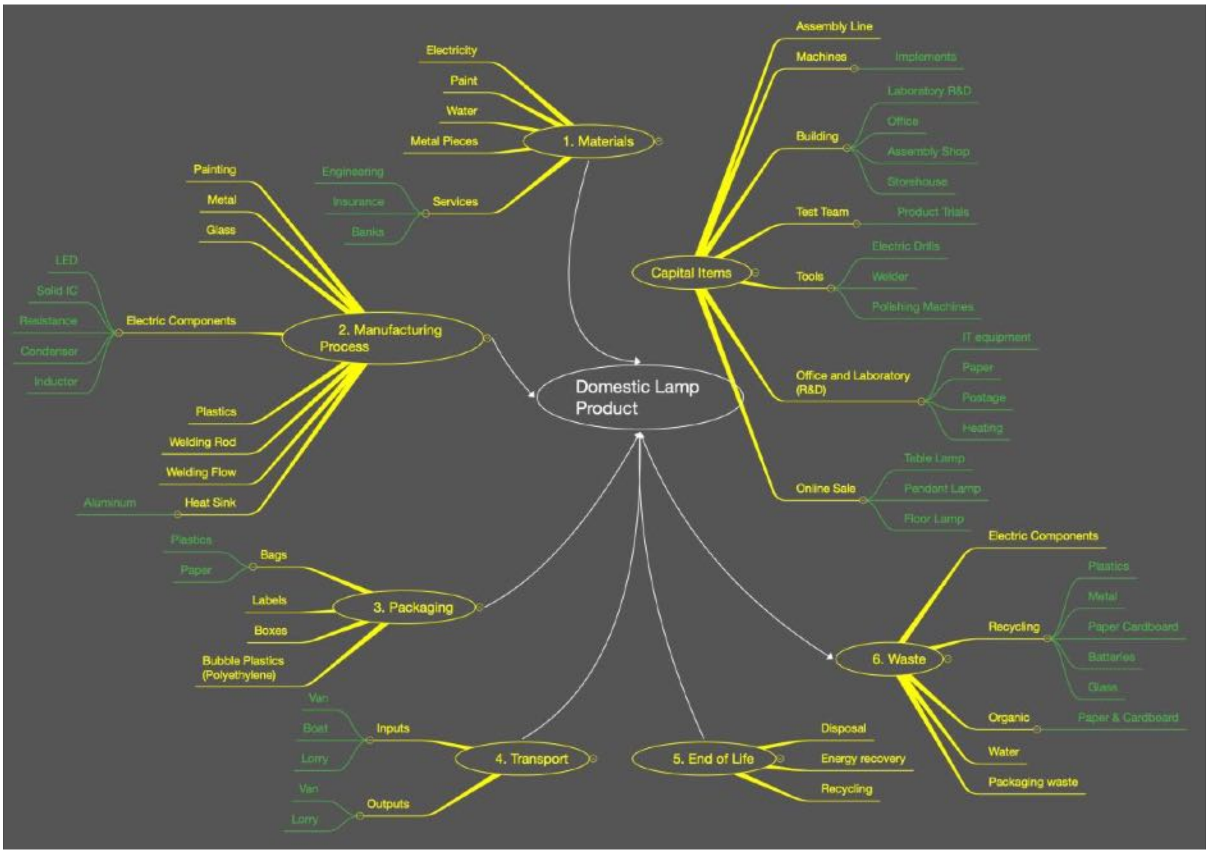

Figure 9-5 ONA's table lamp input/output flowchart.

For the ONA´s table lamp, the main five points showed in Figure 9-5 are considered in the analysis. All inputs are expressed in monetary terms for the SLCA. Thus, final price of the product already covers capital items, overheads and wastes, plus all the materials, capex and labour associated with the production of one functional unit.

For the LCI, mass flows and monetary flows are registered at each step of the production according the flowchart showed in Figure 9-4. Data corresponds to a representative year of the company's activities (2018) and it is complemented with the LCI presented in the study of (Casamayor, Su and Ren, 2018). Then, all reference costs correspond to the reference flows and were estimated by Ona. The LCI is presented in Table 9-5.

Table 9-5 Life cycle inventory of ONA domestic lighting product

Value chain step	Substep	Material/activity	Quantity	Unit	Country Supplier / Waste Destination	Cost €
Reference annual production			300	units		136,11€/unit
Materials	Metal pieces	Virgin stainless steel	2836	g	Spain	70
		Iron	344	g		
	Shade	Parchment	104	g	Spain	59
	Cable	PVC	52	g	Spain	1,68
		Copper	42	g		
	Plug	ABS	7	g	Spain	0,69
		Copper	2	g		
	Lamp frame	ABS	25	g	Spain	0,52
		Cast Iron	3	g		
	Base	Pig iron	872	g	Spain	
	Switch	ABS	7	g	Spain	0,57
		Copper	1	g		
	LED lamp	Iron	12	g	Spain	3,65
		ABS	18	g		
		Aluminium	38	g		
		ABS	1	g		
		PET	11	g		
		Printed Circuit Board (PCB)	5	g		
		LED power supply	3	g		
		Capacitor	4	g		
		Inductors	1	g		
		Resistor	0,6	g		
		Stainless Steel	1	g		
		LED	1	g		
Manufacturing Process	Number of employees dedicated to annual production		2	people	Spain	19800€/year per people

Value chain step	Substep	Material/activity	Quantity	Unit	Country Supplier / Waste Destination	Cost €
Labour	Operator		100	h/year	Spain	18€/h
	Administration		50	h/year	Spain	18€/h
	Transport / Handling		25	h/year	Spain	22€/h
Waste	Recycling	Plastics	91	g	Spain	
		Metal	3180	g	Spain	
		Paper cardboard	104	g	Spain	
	Packaging waste		373	g		
Packaging	Bags	Plastics	1,5	g	Spain	1
		Paper	78	g	Spain	1
	Labels		0,3	g	Spain	0,2
	Boxes		373	g	Spain	5
Transport	Market 2018 Main destination countries	1st Main destination country	100	%	Spain	15
Use	Consumers	Total Electricity consumption in 40.000 hours	268	kWh	Spain	0.145 €/kWh
End of Life	Disposal (domestic bin)		4390	g		
Capital Items	Use of Assembly line dedicated to annual production		100	h/year	Spain	
	Estimated % use of Building dedicated to annual production (considering 100% use for all products)	Laboratory R&D	1	%	Spain	-
		Office	0,25	%	Spain	-
		Assembly shop	6,09	%	Spain	
		Storehouse	0	%	Spain	
		Product trials	1	%	Spain	
	Estimated % use of tools dedicated to annual production (considering 100% use for all products)	Welder	0,2	%	Spain	0,9€/h
		Polishing Machines	0	%	Spain	2,69€/h
	Online Sale	Table lamp	300	units/year		266,20€/unit

The selected product is manufactured about order. Thus, they not have a big stock of the product. Regarding electricity consumption for the manufacturing step, since the product does not have a considerable volume within the company, it was not considered in the LCI. The total number of workers in the company is 4 people. From them, 50% are women. The male median wage is 1,068.37 € and the female median wage is 1,328.44 €. Due the company size, they don´t have obligation to have a labour union. Regarding water consumption, the total consumption per year is 12 m^3 with a cost of 9,31€/m^3. The ratio of annual cost of personnel/annual turnover is 0,75. This value denotes a characteristic of the company where their main activity is the product design. The mean hourly wage paid to employees is 38€/h. It should be mentioned that the cost payed to AMBILAMP for the recycling activity of the product is 0.5€ per unit with corresponds to the extended responsibility of the producer.

Finally, with the aim to assess the ONA´s risk values adapted to its performance, Table 9-6 shows the data collected related to the indicators studied. Since, PSILCA database contains reference data from specific sectors at national level, ONA´s values are used to adapt the reference data to a company level and assuming that this information can be extrapolated to the lighting sector in Spain.

Table 9-6 ONA's social indicator specific data. Source: ONA and Spanish statistics

Stakeholder	Subcategory	Indicator	Unit of measurement	Value
Workers	Fair salary	Living wage, per month	USD	1,449.39 approx..
		Minimum wage, per month	USD	1,003.42 approx.
		Sector average wage, per month	USD	1,114.91 approx.
	Working time	Hours of work per employee, per week	h	20 - 40
	Discrimination	Women in the labour force	% of economically active female population	50
		Men in the labour force	% of economically active male population	50
		Gender wage gap	%	-19.58
	Health and Safety	Accident rate at workplace	#/yr	0
		Fatal accidents at workplace	#/yr	0
		DALYs due to indoor and outdoor air and water pollution	DALYs per 1000 inhabitants in the country	Database
		Presence of sufficient safety measures	OSHA cases per 10000 employees in the setcor	-
		Workers affected by natural disasters	%	-
	Workers´ rights	Trade union density as a % of paid employment total	%	0
		Right of Association	ordinal 0-3	3
		Right of Collective bargaining	ordinal 0-3	3
		Right to Strike	ordinal 0-3	3
Value Chain Actors	Fair competition	Presence of anti-competitive behaviour or violation of anti-trust and monopoly legislation	Cases per 10000 employees in the sector	-
Society	Contribution to economic development	Contribution of the sector to economic development	%	in Spain 1.441 million of € in 2017 lighting sector

Stakeholder	Subcategory	Indicator	Unit of measurement	Value
		Public expenditure on education	USD/yr	in Spain 45,936 million of € in 2017
		Illiteracy rate, male	%	in Spain 1.4%
		Youth illiteracy rate, male	%	0.36
		Illiteracy rate, female	%	in Spain 3,1%
		Youth illiteracy rate, female	%	0.39
		Illiteracy rate, total	%	858,00 people in Spain.
		Youth illiteracy rate, total	%	-
Local Community	Access to material resources	Level of industrial water use, out of total withdrawal	%	-
		Level of industrial water use, out of total actual renewable	%	-
		Extraction (total) of fossil fueles	t/cap	-
		Extraction (total) of biomass	t/cap	-
		Extraction (total) of ores	t/cap	-
		Extraction (total) of biomass	t/km²	-
		Extraction (total) of industrial & const. minerals	t/cap	-
		Presence of certified environmental management systems	# of CEMS per 100000 employees	0
	Safe and healthy living conditions	Pollution level of the country	Text	13,5% -16,5% about
		Contribution of the sector to environmental load	Text	-
		Drinking water coverage	%	100
		Sanitation coverage	%	99
	Local employment	Unemployment rate in the country	%	14,8% about
Consumers	Health and Safety	Violations of mandatory health and safety standards	#	-
	End of life responsibility	Strength of national legislation covering product disposal and recycling	Text	ONA belongs to AMBILAMP that is in charge of the collection and recycling of electric product.

9.3.4 Social Life Cycle Impact Assessment

Based on: i) the social categories and indicators definition approach, ii) finding out the level of importance of each subcategory for the company and for the company customers and stakeholders with a materiality analysis and iii) by developing the life cycle inventories of input/output per process (including calculation of the process inputs in 2011 US$ in order to refer to PSILCA database), the social life cycle assessment of the reference products has been conducted following the steps below:

- Specific social data collection from company and sector to assess the level of risk for each selected indicator.
- Calculation of the worker hours of the main activity in hours per $ of output. This is calculated as a ratio of the unit labour costs ($/h) and the mean hourly wage per employee, as presented below:
  - Construct the simulation models in openLCA, using self-made processes supported by the built-in industries and commodities available per country and sector in PSILCA.
  - Perform the LCI assessment by simulation using openLCA.
  - Interpret the results.
  - Adjust model and iterate.

The ratio of annual cost of personnel/annual turnover is 0,75 for the reference year and the mean hourly labour cost per employee is 38€/h (42 US$/h considering a exchange rate of 0,897 €/US$), the worker hours of the main activity (in hours per $ of output) is 0,01770 h/US$. In order to have a comparable value with PSILCA database ones, the exchange rate considered for 2011 US$ is 0.75 €/US$. As explained previously, we neglect differences between the two currencies' depreciation rates, as both economies have had similar inflation levels in the period. Thus, the worker hours of the main activity (in hours per $ of output) for 2011 is 0,01480 h/US$. This is higher than PSILCA's value for the reference sector in Spain: Manufacture of domestic appliances/Commodities/Spain (0,01028 h/US$). Other reference sectors where the worker hours of the main activity are lower than ONA could be: Manufacture of lighting equipment and electric lamps/Commodities/ Great Britain (0,01020 h/US$), Electric lamp bulb and part manufacturing/Commodities/United States (0,01012 h/US$), Lamp & lighting fixtures/Commodities/Singapore (0,002369 h/US$) and

Electric lamps and lighting equipment/Commodities/Taiwan (0,009456 h/US$). On the other hand, ONA´s worker hours of the main activity are lower than Incandescent electric lamps or discharge, arc lamps, electric lighting equipment, and parts and pieces/Commodities/Argentina (0,09039 h/US$). After a deep analysis comparing the aforementioned reference sectors in PSILCA (mainly geographic and socio-economic situation in each country) and considering that the Spanish reference sector is not specifically related only with the lighting sector, it has been selected the Manufacture of domestic appliances/Commodities/Spain as reference sector for the analysis in this report. The aim is to make a comparative analysis evaluating the changes of the database in risk assessment and worker hours (h/US$) and considering also the module created in SimaPro software with ONA´s LCI.

In this sense, the analysis starts by calculating the PSILCA metrics for risk assessment of the company ONA in the Spanish lighting sector. Each of the indicators selected are classified by scope (national, sectoral, or company-specific) and then by existence in PSILCA database. The relative importance level for the company and its stakeholders have been considered related to manufacturing and packaging, transport, use and end-of-life activities (included in the materiality analysis). The indicator index is calculated according to the PSILCA database definition and compared against the risk level factors to assign risk levels, the results of which are presented in Table 9-7.

Table 9-7 ONA’s risk level assessment matrix

Indicator	Unit of measurement	SCALE	PSILCA RISK ASSESMENT	Metric value	ONA's risk
Living wage, per month	USD	Nation	. Evaluation scheme: <100 = very low risk; 100-<200 = low risk; 200-<500 = medium risk; 500-<1000 = high risk; >1000 = very high risk; n.a. = no data	500	Medium risk
Minimum wage, per month	Ratio	Nation	. Evaluation scheme: Data for LW is available: LW-MW-ratio>=1,2 OR ratio>=1 and MW<300USD = very high risk; ratio=1-<1,2 and MW>=300USD OR ratio=0,8-<1 and MW<300USD = high risk; ratio=0,8-<1 = medium risk and MW>300USD; ratio=0,5-<0,8 = low risk; ratio<0,5 = very low risk; Where no data for living wage available: <200USD = very high risk; 200-<300USD = high risk; 300-<500USD = medium risk; 500-<1000USD = low risk; >=1000USD = very low risk; n.a. = no data	1.11	Medium risk
Sector average wage, per month	Ratio	Sector	Evaluation scheme: If living wage (LW) for country is available OR if only mean of living wage is available (and no minimum wage), then scale refers to ratio Sector average wage (S)/LW. If no value for LW available but for minimum wage (MW), then scale refers to ratio S/MW: <1 = very high risk; 1 -< 1.5 = high risk; 1.5 -< 2 = medium risk; 2 -< 2.5 = low risk; >= 2.5 = very low risk; no data	1.5	Medium risk
Hours of work per employee, per week	h	Company	Explanation of unit of measurement: Hours of work per employee and week. Evaluation scheme: 40 - <48 = low risk; 30 - <40 and 48 - <55 = medium risk; 20 - <30 and 55 - <60 = high risk; <20 and >60 = very high risk; n.a.= no data	40	Low risk
Women in the labour force	% of economically active female population	Sector	Explanation of unit of measurement: Ratio between the share of women employed in a sector out of total active female population in a country and the share of men and women working in the same sector out of total active population in the country. Evaluation scheme: 1 = no risk; 0.8-<1 or >1-1.5 = very low risk; 0.6-<0.8 or >1.5 = low risk; 0.4-<0.6 = medium risk; 0.2-<0.4 = high risk; <0.2 = very high risk; not applicable; no data	50	medium risk
Men in the labour force	% of economically	Sector	Explanation of unit of measurement: Ratio between the share of men employed in a sector out of total active male population in a country and the share of men and women working in the same sector out of total active	50	Very low risk

Indicator	Unit of measurement	SCALE	PSILCA RISK ASSESMENT	Metric value	ONA's risk
	active male population		population in the country. Evaluation scheme: 1 = no risk; 0.8-<1 or >1-1.5 = very low risk; 0.6-<0.8 or >1.5 = low risk; 0.4-<0.6 = medium risk; 0.2-<0.4 = high risk; <0.2 = very high risk; not applicable; no data		
Gender wage gap	%	Company	Explanation of unit of measurement: Difference between male and female median wages divided by the higher median wage*100; expressed in %. Evaluation scheme: 0% = no risk; 0% - <5% and 0% - >-5%= very low risk; 5% - <10% and -5% - >-10% = low risk; 10% - <20% and -10% - >-20% = medium risk; 20% - <30% and -20% - >-30% = high risk; >=30% and <=-30 = very high risk; n.a. = no data	-19,58	Medium risk
Accident rate at workplace	#/year	Company	Explanation of unit of measurement: Number of non-fatal accidents per 100,000 employees and year. Evaluation scheme: 0-<750 = very low risk; 750-<1500 = low risk; 1500-<2250 = medium risk; 2250-<3000 = high risk; >3000 = very high risk; no data	0	Very low risk
Fatal accidents at workplace	#/year	Company	Explanation of unit of measurement: Number of fatal accidents per 100,000 employees and year. Evaluation scheme: 0-<7,5 = very low risk; 7,5-<15 = low risk; 15-<25 = medium risk; 25-<40 = high risk; >40 = very high risk; no data	0	Very low risk
DALYs due to indoor and outdoor air and water pollution	DALYs per 1000 inhabitants in the country	Nation	Explanation of unit of measurement: Disability adjusted life years (DALYs) per 1,000 inhabitants in the country. Evaluation scheme: 0= no risk; >0-<5 = very low risk; 5-<15 = low risk; 15-<30 medium risk; 30-<50 high risk; >50 very high risk; n.a. = no data	PSILCA	
Presence of sufficient safety measures	OSHA cases per 100000 employees in the sector	Sector	Explanation of unit of measurement: Number of violations of occupational safety and health standards (=OSHA cases) per 100,000 employees in the sector. Evaluation scheme: 0 < 100 = very low risk; 100 - < 300 = low risk; 300 - < 600 = medium risk; 600 - < 1000 = high risk; > 1000 = very high risk; no data	0	Very low risk
Workers affected by natural disasters	%	Nation	Explanation of unit of measurement: Persons affected between 2012 and 2014 as percentage of whole population. Evaluation scheme: 0-<1 = very	0	Very low risk

Indicator	Unit of measurement	SCALE	PSILCA RISK ASSESMENT	Metric value	ONA's risk
			low risk; 1-<3 = low risk; 3-<5= medium risk, 5-<10 = high risk; >=10 = very high risk; n.a. = no data		
Trade union density as a % of paid employment total	%	Company	Explanation of unit of measurement: Percentage of employees organised in trade unions. Evaluation scheme: 0-20% = very high risk; >20-40% = high risk; >40-60% = medium risk; >60-80% = low risk; >80% = very low risk	20	high risk
Right of Association	ordinal 0-3	Nation	Explanation of unit of measurement: ordinal 4 point scale (0-3). Evaluation scheme: 3 = no risk; 2 = low risk; 1 = high risk; 0 = very high risk; no data	3.00	No risk
Right of Collective bargaining	ordinal 0-3	Nation	Explanation of unit of measurement: ordinal 4 point scale (0-3). Evaluation scheme: 4 = no risk; 2 = low risk; 1 = high risk; 0 = very high risk; no data	3.00	No risk
Right to Strike	ordinal 0-3	Nation	Explanation of unit of measurement: ordinal 4 point scale (0-3). Evaluation scheme: 5 = no risk; 2 = low risk; 1 = high risk; 0 = very high risk; no data	3.00	No risk
Contribution of the sector to economic development	%	Sector	Explanation of unit of measurement: Shares of breakdown of GDP/Value Added at current prices in percent; if value is derived from the Mining contribution index it expresses the Metallic mineral and coal production value 2014 (as % of GDP).. Evaluation scheme: 0-<1 = no opportunity; 1-10 = low opportunity; >10-25 = medium opportunity; >25 = high opportunity; no data	Less than 1%	No opportunity
Public expenditure on education	US$/y	Nation	Explanation of unit of measurement: Percentage of GDP in a given year. Evaluation scheme: 0 - < 2,5% = very high risk; 2,5-<5% = high risk; 5-<7,5% = medium risk; 7,5-<10% = low risk; >=10% = very low risk; n.a. = no data	5%	Medium risk
Illiteracy rate, male	%	Nation	Explanation of unit of measurement: Percentage of male population. Evaluation scheme: 0 - <1% = very low risk; 1 - <4% = low risk; 4 - <8% = medium risk; 8- <15% = high risk; >=15% = very high risk; n.a. = no data	1.4%	Very low risk
Youth illiteracy rate, male	%	Nation	Explanation of unit of measurement: Percentage of male population, ages 15-24. Evaluation scheme: 0 - <1% = very low risk; 1 - <4% = low risk; 4 - <8% = medium risk; 8- <15% = high risk; >=15% = very high risk; n.a. = no data	0.4%	Very low risk

Indicator	Unit of measurement	SCALE	PSILCA RISK ASSESMENT	Metric value	ONA's risk
Illiteracy rate, female	%	Nation	Explanation of unit of measurement: Percentage of female population. Evaluation scheme: 0 - <1% = very low risk; 1 - <4% = low risk; 4 - <8% = medium risk; 8- <15% = high risk; >=15% = very high risk; n.a. = no data	3.1%	Low risk
Youth illiteracy rate, female	%	Nation	Explanation of unit of measurement: Percentage of female population, ages 15-24. Evaluation scheme: 0 - <1% = very low risk; 1 - <4% = low risk; 4 - <8% = medium risk; 8- <15% = high risk; >=15% = very high risk; n.a. = no data	0.4%	Very low risk
Illiteracy rate, total	%	Nation	Explanation of unit of measurement: Percentage of total population. Evaluation scheme: 0 - <1% = very low risk; 1 - <4% = low risk; 4 - <8% = medium risk; 8- <15% = high risk; >=15% = very high risk; n.a. = no data	1.8%	Low risk
Youth illiteracy rate, total	%	Nation	Explanation of unit of measurement: Percentage of total population, ages 15-24. Evaluation scheme: 0 - <1% = very low risk; 1 - <4% = low risk; 4 - <8% = medium risk; 8- <15% = high risk; >=15% = very high risk; n.a. = no data	0.4%	Very low risk
Pollution level of the country	Text	Nation	Explanation of unit of measurement: Pollution Index based on perceptions. Evaluation scheme: 0-20 = very low risk; 20-40 = low risk; 40-60 = medium risk; 60-80 = high risk; >80 = very high risk; n.a. = no data	PSILCA	
Contribution of the sector to environmental load CO2	Text	Sector	Explanation of unit of measurement: kg, emission to air, total, CO2 equivalents, IPCC 2006. Evaluation scheme: 0 - 1e-5 = very low risk; >1e-5 - 1e-4 = low risk; >1e-4 - 1e-3 = medium risk; >1e-3 - 1e-2 = high risk; >1e-2 = very high risk; no data	no data	n.a.
Drinking water coverage	%	Nation	Explanation of unit of measurement: Percentage of the population with access to drinking water. Evaluation scheme: <=85% = very high risk; >85% - 92% = high risk; >92% - 97% = medium risk; >97% - <100% = low risk; 100% = very low risk; n.a. = no data	100	Very low risk
Sanitation coverage	%	Nation	Explanation of unit of measurement: Percentage of the population with access to sanitation facilities. Evaluation scheme: <=85% = very high risk; >85% - 92% = high risk; >92% - 97% = medium risk; >97% - <100% = low risk; 100% = very low risk; n.a. = no data	99	Low risk

Indicator	Unit of measurement	SCALE	PSILCA RISK ASSESMENT	Metric value	ONA's risk
Level of industrial water use, out of total withdrawal	%	Company	Explanation of unit of measurement: Industrial water withdrawal as percentage of total withdrawal per year. Evaluation scheme: 0 - <10% = very low risk; 10 - < 20% = low risk; 20 - <30% = medium risk; 30 - <40% = high risk; >= 40% = very high risk; n.a. = no data	Less than 5%	Very low risk
Level of industrial water use, out of total actual renewable	%	Company	Explanation of unit of measurement: Industrial water withdrawal as percentage of total actual renewable water resources. Evaluation scheme: 0 - <1% = very low risk; 1 - <3% = low risk; 3 - <7% = medium risk; 7 - <13% = high risk; >= 13% = very high risk; n.a. = no data	Less than 5%	Medium risk
Extraction (total) of fossil fueles	t/cap	Company	Explanation of unit of measurement: total extraction in t/capita in 2011. Evaluation scheme: 0 - <10 = very low risk; 10 - <20 = low risk; 20 - <30 = medium risk; 30 - <50 = high risk; >=50 = very high risk; n.a. = no data	0	Very low risk
Extraction (total) of biomass related to area	t/m2	Company	Explanation of unit of measurement: total extraction in t/km² in 2011. Evaluation scheme: 0 - <200 = very low risk; 20 0- <400 = low risk; 40 0- <600 = medium risk; 60 0- <800 = high risk; >=800 = very high risk; n.a. = no data	0	Very low risk
Extraction (total) of ores	t/cap	Company	Explanation of unit of measurement: total extraction in t/capita in 2011. Evaluation scheme: 0 - <5 = very low risk; 5 - <10 = low risk; 10 -<15 = medium risk; 15 - <20 = high risk; >=20 = very high risk; n.a. = no data	0	Very low risk
Extraction (total) of biomass related to population	t/cap	Company	Explanation of unit of measurement: total extraction in t/capita in 2011. Evaluation scheme: 0 - <2,5 = very low risk; 2,5 - <5 = low risk; 5 - <10 = medium risk; 10 - <15 = high risk; >=15 = very high risk; n.a. = no data	0	Very low risk
Extraction (total) of industrial & const. minerals	t/cap	Company	Explanation of unit of measurement: total extraction in t/capita in 2011. Evaluation scheme: 0 - <2,5 = very low risk; 2,5 - <5 = low risk; 5 - <10 = medium risk; 10 - <15 = high risk; >=15 = very high risk; n.a. = no data	0	Very low risk
Presence of certified environmental management systems	# CEMS per 10000 employee	Sector	Explanation of unit of measurement: Number of Certified environmental management systems (CEMS) (ISO 14001) in sector per 10,000 employees in the country. Evaluation scheme: >=100 = very low risk; 10-<100 = low risk; 1-<10 = medium risk; 0,3-<1 = high risk; 0-<0,3 very high risk; n.a. = no data	0	Very high risk

Indicator	Unit of measurement	SCALE	PSILCA RISK ASSESMENT	Metric value	ONA's risk
Unemployment rate in the country	%	Nation	Explanation of unit of measurement: Percentage of the population. Evaluation scheme: 0% - < 3% = very low risk; 3% - <8% = low risk; 8% - <15% = medium risk; 15 - <25 = high risk; >= 25% = very high risk; n.a. = no data	11.2%	medium risk
Violations of mandatory health and safety standards	#	Sector	Explanation of unit of measurement: Violation cases (of wage and hour compliance) per 1,000 employees in the sector between 2007 and 2014. Evaluation scheme: <0,1 = very low risk; 0,1 - <1 = low risk; 1 - <10 = medium risk; 10 - <100 = high risk; >100 = very high risk; n.a. = no data	-	no risk
Presence of anti-competitive behaviour or violation of anti-trust and monopoly legislation	Cases per 10000 employees in the sector	Sector	Explanation of unit of measurement: Violation cases (of wage and hour compliance) per 1,000 employees in the sector between 2007 and 2014. Evaluation scheme: <0,1 = very low risk; 0,1 - <1 = low risk; 1 - <10 = medium risk; 10 - <100 = high risk; >100 = very high risk; n.a. = no data	PSILCA	

9.3.5 Results and discussion

Social impacts are weighed as per the risk level according to Table 9-8, which corresponds to the PSILCA Social Life Cycle Impact Analysis method v1.00 by using in openLCA software.

Table 9-8 PSILCA risk level weights. (PSILCA Social Life Cycle Impact Analysis method v1.00)

RISK LEVEL	WEIGHT
VERY HIGH RISK	5
HIGH RISK	2
MEDIUM RISK	1
LOW RISK	0.5
VERY LOW RISK	0.25
NO RISK	0
NO DATA	0.5

Table 9-9 and Figure 9-6 show the results of the SLCA of the table lamp performing the LCI assessment. It should be mentioned that the LCI in monetary terms has been worked out. Thus, all cost values and product price were converted into 2011's US$ using the 0.75 €/US$ exchange rate.

Table 9-9 ONA´s LED domestic table lamp SLCA absolute results per impact indicator

Impact Category	Unit	Total	Cable	Lamp frame	LED lamp	Metal pieces	Plug	Shade	Switch	Packaging	Manufacture of domestic appliances /Commodities /ES	Other transport material n.e.c./ Commodities/ES	Other business services/ Commodities/ ES	Production and distribution of electricity/ Commodities/ ES	Recycling /Industries/ ES
Minerals consumption	MC med risk	30.17	0.33	0.05	0.32	6.35	0.10	8.95	0.07	1.04	1.42	0.88	7.85	2.73	0.05
Non-fatal accidents	NFA med risk	64.17	0.42	0.14	0.85	17.86	0.18	16.52	0.15	2.01	3.31	1.91	14.70	6.01	0.12
DALYs indoor/outdoor air & water pollut.	DALY med ris	7.90	0.08	0.01	0.08	1.51	0.02	2.80	0.02	0.32	0.34	0.21	1.86	0.64	0.02
Association and bargaining rights	ACB med risk	20.31	0.43	0.03	0.16	2.93	0.11	9.17	0.06	1.02	0.60	0.58	4.13	1.07	0.03
International migrant stock	IMS med risk	34.88	0.26	0.06	0.40	8.18	0.10	8.25	0.07	0.99	1.68	1.03	10.08	3.72	0.06
Youth illiteracy	YI med risk	27.82	0.28	0.04	0.25	5.11	0.08	10.61	0.06	1.19	1.15	0.68	6.19	2.11	0.06
Weekly hours of work per employee	WH med risk	20.08	0.14	0.03	0.21	4.45	0.05	5.45	0.04	0.64	0.95	0.57	5.53	1.97	0.04
Violations of employ. laws & regulations	VL med risk	30.71	0.24	0.05	0.36	6.53	0.08	9.44	0.06	1.09	1.35	0.97	7.48	3.00	0.05
Net migration	NM med risk	15.63	0.12	0.03	0.19	3.90	0.04	3.35	0.03	0.41	0.76	0.42	4.57	1.79	0.03
Indigenous rights	IR med risk	16.00	0.19	0.02	0.12	2.14	0.05	8.17	0.03	0.90	0.44	0.42	2.80	0.69	0.03
Pollution	P med risk h	25.62	0.39	0.04	0.23	4.54	0.11	9.98	0.07	1.12	1.12	0.71	5.51	1.75	0.05
Frequency of forced labour	FL med risk	7.15	0.07	0.01	0.07	1.42	0.02	2.50	0.02	0.28	0.26	0.19	1.69	0.61	0.02
Goods produced by forced labour	GFL med risk	0.73	0.01	0.00	0.01	0.09	0.00	0.34	0.00	0.04	0.01	0.01	0.15	0.05	0.00
Anti-competitive behaviour	AC med risk	11.44	0.11	0.02	0.12	2.51	0.04	3.38	0.03	0.39	0.55	0.30	2.98	1.00	0.02
Corruption	C med risk h	92.81	0.86	0.16	1.17	20.82	0.28	29.96	0.21	3.45	4.74	2.47	20.83	7.70	0.17
Illiteracy	I med risk h	60.28	0.67	0.09	0.54	10.99	0.19	23.77	0.13	2.66	2.27	1.39	12.96	4.48	0.14
Fossil fuel consumption	FF med risk	7.44	0.07	0.01	0.07	1.45	0.02	2.46	0.02	0.28	0.41	0.22	1.81	0.60	0.01
Workers affected by natural disasters	ND med risk	9.31	0.15	0.01	0.09	1.76	0.04	3.24	0.03	0.37	0.42	0.27	2.21	0.71	0.02
Internt. migrant workers. in sector/site	IMW med risk	32.07	0.25	0.05	0.36	7.44	0.08	8.27	0.06	0.96	1.27	1.01	9.05	3.22	0.06
Unemployment	U med risk h	68.17	0.39	0.13	0.88	18.22	0.17	12.06	0.14	1.52	3.42	1.85	20.68	8.57	0.13
Biomass consumption	BM med risk	59.93	0.48	0.09	0.58	11.43	0.16	20.71	0.12	2.36	2.33	1.74	14.97	4.84	0.11
Child Labour	CL med risk	23.74	0.44	0.03	0.19	3.50	0.11	11.07	0.07	1.23	1.07	0.55	4.30	1.14	0.04

Impact Category	Unit	Total	Cable	Lamp frame	LED lamp	Metal pieces	Plug	Shade	Switch	Packaging	Manufacture of domestic appliances /Commodities /ES	Other transport material n.e.c./ Commodities/ES	Other business services/ Commodities/ ES	Production and distribution of electricity/ Commodities/ ES	Recycling /Industries/ ES
Drinking water coverage	DW med risk	14.14	0.14	0.02	0.13	2.48	0.04	5.52	0.03	0.62	0.99	0.37	2.84	0.92	0.03
Education	E med risk h	41.53	0.36	0.07	0.46	9.21	0.12	11.66	0.09	1.36	1.99	1.13	10.92	4.07	0.08
Fair Salary	FS med risk	86.23	1.01	0.13	0.83	16.46	0.30	30.57	0.20	3.47	3.79	2.23	20.37	6.71	0.16
Safety measures	SM med risk	36.47	0.43	0.09	0.43	10.94	0.15	10.33	0.12	1.27	1.43	1.00	7.32	2.87	0.09
Gender wage gap	GW med risk	45.86	0.28	0.07	0.37	8.49	0.11	13.46	0.08	1.55	1.63	1.02	14.98	3.71	0.10
Trafficking in persons	TP med risk	15.64	0.21	0.02	0.14	2.72	0.06	6.12	0.04	0.69	1.03	0.37	3.22	1.00	0.03
Fatal accidents	FA med risk	9.92	0.10	0.02	0.11	1.91	0.03	3.55	0.02	0.40	0.41	0.30	2.30	0.76	0.02
Social security expenditures	SS med risk	25.77	0.36	0.04	0.22	4.40	0.10	10.66	0.06	1.19	0.99	0.64	5.33	1.73	0.05
Industrial water depletion	WU med risk	43.37	0.38	0.07	0.43	8.40	0.12	13.82	0.09	1.59	2.33	1.51	11.03	3.51	0.07
Trade unionism	TU med risk	99.28	0.66	0.17	1.11	22.19	0.25	27.40	0.20	3.22	4.47	2.81	26.74	9.88	0.19
Sanitation coverage	SC med risk	42.55	0.49	0.06	0.33	6.29	0.14	20.22	0.10	2.25	1.43	0.92	8.07	2.17	0.07
Health expenditure	HE med risk	76.42	0.71	0.12	0.76	15.32	0.23	25.97	0.16	2.97	3.31	1.87	18.38	6.46	0.15
Certified environmental management syst.	CMS med risk	76.22	0.55	0.10	0.57	11.78	0.18	26.35	0.13	2.97	3.67	2.41	21.66	5.71	0.14

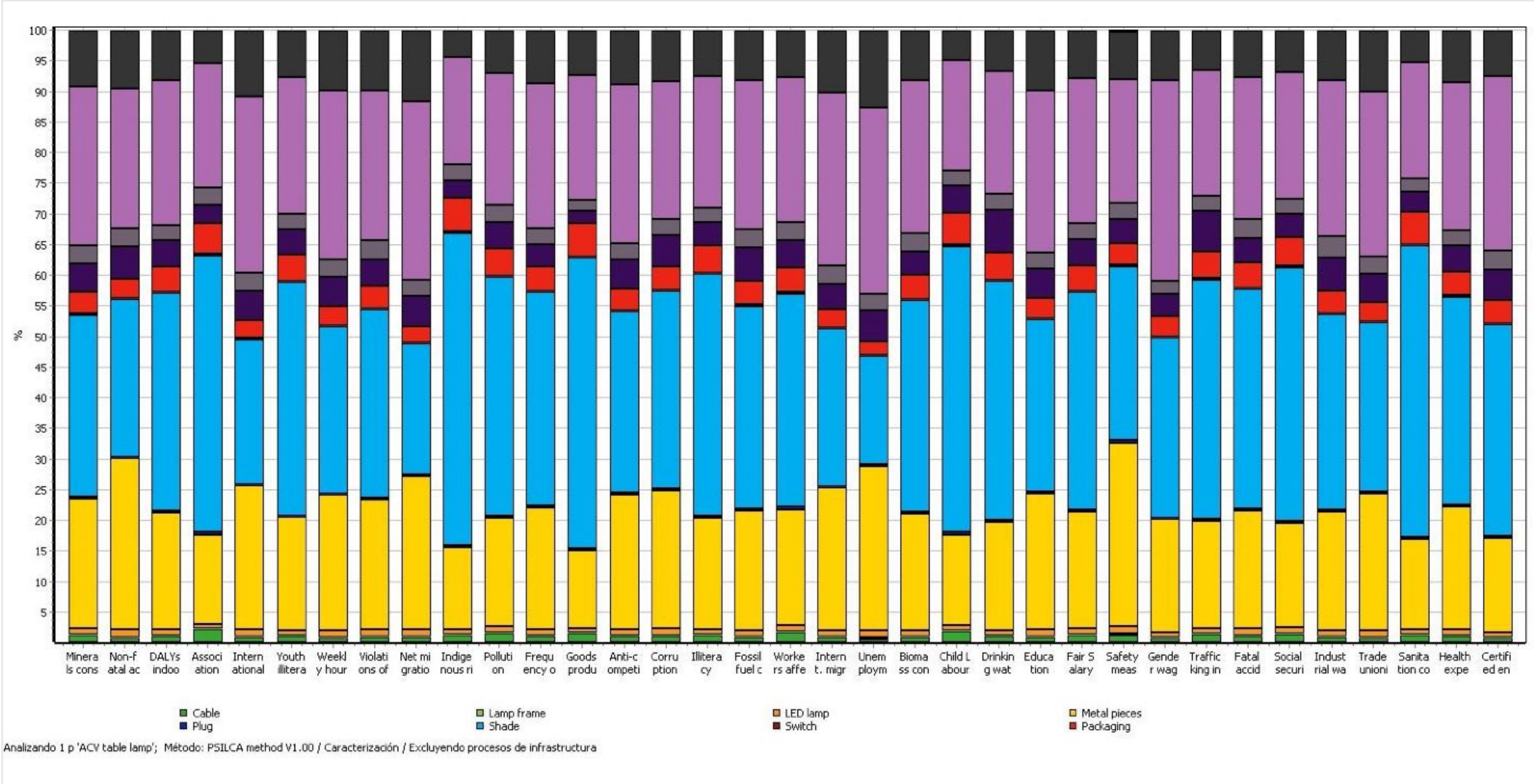

Figure 9-6 Contribution of the stages in ONA´s domestic LED table lamp SLCA results

As can be seen in Figure 9-6, the metal pieces plus the shade represent more than 45% if the impact in all social impact categories. The category of 'Other business services/Commodities/ES' (represented in purple) also represents an important part of the impact. This category represents the 'indirect costs', which are all costs related to business activities as the difference between the final price and all the cost stated in LCI. In this case, the indirect costs estimated for the table lamp is 109.6 US$ which represents 37% of the final price of the product. It should be mentioned that an important part of this percentage corresponds to the commercial margin of the company. In addition, use phase (electricity consumption during 40.000 hours of lifetime) corresponds to 51,9 US$ being the fourth most important variable in terms of social impact.

In order to compare these results with the Spanish representative sector in PSILCA, Table 9-10 and Figure 9-7 shows the comparative results of the table lamp SLCA and the Manufacture of domestic appliances/Commodities/Spain. It should be mentioned that for the reference sector, the worker hours estimated for ONA of 0.01480 h/US$ and ONA´s risk levels factors for the indicators studied (Table 9-7) were considered. In addition, since PSILCA database covers a cradle to gate approach, comparison is made accordingly.

Table 9-10 Comparative results of the table lamp SLCA vs PSILCA reference sector

Impact Category	Unity	Manufacture of domestic appliances/Commodities/ES	SLCA table lamp w/o use
Minerals consumption	MC med risk	16.97	27.44
Non-fatal accidents	NFA med risk	17.85	58.16
DALYs indoor/outdoor air & water pollut.	DALY med ris	3.96	7.26
Association and bargaining rights	ACB med risk	6.26	19.24
International migrant stock	IMS med risk	20.85	31.17
Youth illiteracy	YI med risk	13.26	25.71
Weekly hours of work per employee	WH med risk	9.00	18.12
Violations of employ. laws & regulations	VL med risk	15.79	27.70
Net migration	NM med risk	9.55	13.84
Indigenous rights	IR med risk	4.57	15.31
Pollution	P med risk h	12.59	23.87
Frequency of forced labour	FL med risk	3.14	6.54
Goods produced by forced labour	GFL med risk	0.15	0.67
Anti-competitive behaviour	AC med risk	6.55	10.44
Corruption	C med risk h	54.59	85.11
Illiteracy	I med risk h	24.94	55.80
Fossil fuel consumption	FF med risk	4.71	6.84
Workers affected by natural disasters	ND med risk	4.79	8.60
Internt. migrant workers. in sector/site	IMW med risk	15.00	28.85
Unemployment	U med risk h	22.94	59.60
Biomass consumption	BM med risk	27.67	55.10
Child Labour	CL med risk	11.22	22.61
Drinking water coverage	DW med risk	10.79	13.21

Education	E med risk h	24.15	37.46
Fair Salary	FS med risk	51.67	79.52
Safety measures	SM med risk	9.03	33.60
Gender wage gap	GW med risk	15.06	42.15
Trafficking in persons	TP med risk	11.19	14.64
Fatal accidents	FA med risk	4.68	9.16
Social security expenditures	SS med risk	11.20	24.04
Industrial water depletion	WU med risk	25.62	39.86
Trade unionism	TU med risk	54.95	89.39
Sanitation coverage	SC med risk	16.79	40.38
Health expenditure	HE med risk	39.20	69.95
Certified environmental management syst.	CMS med risk	46.54	70.51

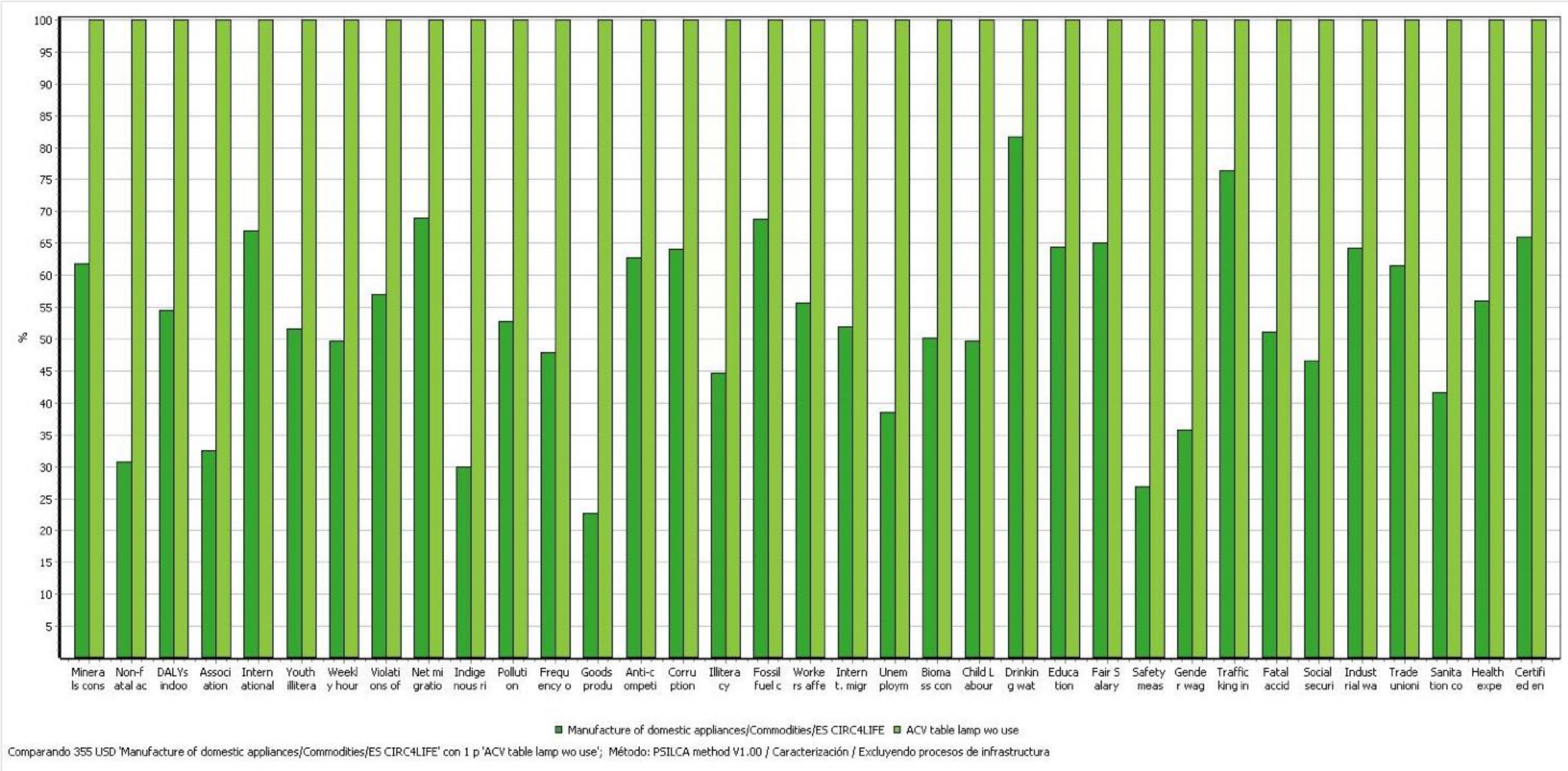

Figure 9-7 The table lamp (ONA) SLCA vs PSILCA reference sector

Based on the results of the SLCA of 1 unit of table lamp (domestic lighting product) through their lifecycle; this chapter presents the main findings and recommendations for this product. It should be mentioned that these results are presented on a static assessment basis. This means that the different assessments are based on a reference product and production year setting a reference scenario for the future assessment of innovation solutions.

Through the materiality analysis, it was identified the Access to material resources (local community), Health and Safety (consumers), fair salary (workers) and contribution to economic development (society) are among the subcategories with a high significance for ONA in relation with the product analysed. In addition, they have also identified the access to material resources (local community) and Health and Safety (consumers) as relevant subcategories with a high influence on stakeholders' perceptions of the product. Risk estimation made in the Social Life Cycle Impact assessment evaluate the aforementioned categories pointing out the following:

- The presence of certified environmental management systems has a value of very high risk. A certification in environmental management systems (CEMS) (e.g. ISO 14001) is recommended to improve this score.
- The Level of industrial water use has a better score (very low risk vs low risk) in comparison to the reference sector in PSILCA.
- The low percentage of employees organised in trade unions has a score of very high risk, that can be improved promoting related activities in the company.
- The null ratio of accidents at workplace has a very low risk score in comparison to the reference sector in PSILCA. Internal activities to maintain this ratio is recommended.
- Even gender wage gap has a negative value (-19,58%) this represents a medium risk in social terms. However, still being a better score in comparison to the reference sector in PSILCA (high risk).

Regarding the SLCA results, attention should be paid during the selection of materials for the proposed innovation, mainly those related to replace or improve the scores of the metal pieces (mainly virgin stainless steel and Iron) and the shade. In addition, it must be taken into account that indirect costs (including commercial margin) have a representative impact in each indicator studied.

This is a characteristic of this sector where products are designed in ONA and then send to the providers for its manufacturing. Finally, due the use phase has also a representative impact in the results, options with a lower power of lamp could improve the final scores.

Chapter 10: Conclusions

This thesis presents the doctoral research performed in sustainability (environmental and social) studies. The activities also aimed to contribute to the goals of the EU FP7 cycLED project and had three main objectives:

- Review the needs of stakeholders in addressing the complex eco-design methods associated with LED lighting products through the lifecycle;
- Development of an integrated approach for sustainable lighting product development process including product design specification, conceptual design, detail design, prototyping and test and manufacture.
- Develop a conceptual integrated eco-decision approach framework for engineers and sustainability assessment of LED lighting products based on stakeholders' needs and a case study to demonstrate such an approach;
- Apply the integrated approach and related methods into the development of a sustainable LED lighting products.

All the above objectives have been achieved. The value of this research is most evident in case study application, where trade-offs between innovation, eco-design and environmental and social impacts could be better understood and prescription for improving the sustainability of sustainable LED lighting products. The summary interpretation of the environmental and social LCA studies is in agreement with the intuition of product experts, and a systematic approach to case study application is demonstrated that would enable stakeholders to achieve important insights during early sustainable product development.

10.1 Discussion

10.1.1 Limitations of the research

The research reported in this thesis has involved several research areas which are highly complex and diverse in their scopes. Research into assessing a company's or product's environmental and social performances has somewhat divided the business practices and their responsibilities. This research has extended these to benefits and identified how this can be incorporated at a sustainable product development and at the corporate level through using the developed integrated eco-design approach and the Toolkit.

The limitations of this study have been explained throughout the thesis. However, there are a few more limitations which need to be discussed and clarified due to the time and resources available, which are described as below:

- Lack of access to updated data surrounding the lighting product transportation process in the environmental LCA studies.
- Investigation into the social impacts associated with LED lighting lamp use stage was not fully considered as the consumers feedback are difficult to obtain.
- Comprehensive and varied case studies assessing the ease of the developed toolkit and eco-design method within a broader range of products was not carried out.
- The proposed Sustainable Production Support Toolbox including the LCA technologies, standards of environmental management system, and the EU regulations and directives, which are all updated in a regular time period, particularly, the regulations and directives usually have a variety of amendments.
- Detailed consideration of future legislation and its potential impact on current resource consumption and material supply was not considered sufficiently.

10.1.2 Research contributions

The author has identified the following as the important contributions made by this research in the area of sustainability assessment and eco-design for sustainable product development:

- Highlighting the significant advantages in environmental life cycle assessment, which not only can be used to compare products' environmental performance, but also for products design process.
- Extending the scope of existing eco-design knowledge and tools on sustainable product development by integrating the requirements of manufacturing and supply chain, along with those from regulations, resulting from the extensive review in available literatures and project resources for new products.

- Definition of a novel integrated approach for assessing the environmental performance of a product through its life cycle.
- Demonstration of a comprehensive societal assessment framework and associated assessment methods to provide a means of ensuring product development can be directed towards the manufacture of products with the greatest societal benefits.
- Development of an eco-design design Toolkit to support the implementation and integration of the environmental LCA framework within a sustainable product development.

10.2 Conclusions

The literature review of current environmental and social LCA methods and case studies clearly identifies a capability gap in their ability to form a comprehensive sustainability assessment. This is due partly to the current lack of framework for practitioners to balance the current business model of consumer demand and to the fundamental basis upon which LCA methodology is built.

A number of tools have been developed and made available to industry to support their activities to develop more sustainable products and conduct sustainable production. These tools focus primarily on assessing the environmental and to a lesser degree of applying eco-design methods. What they fail to address is the fundamental phase where the environmental performance of a product life cycle can be addressed more efficiently. The integrated eco-design toolkit developed in this research supports the implementation and integration of the eco-design tools and methods within the sustainable product design process, therefore it is beneficial for the company to consider products sustainability performance in their overall business activities.

The integrated eco-design approach reported in this thesis provides a comprehensive approach to provide state of art tools and methods for the development of sustainable products and allowing the comparison of products with different materials or designs to be made. The included methods and tools for supporting the implementation of the integrated framework provides a systematic approach for each of product development phases. The development of this method is also validated by the development of a commercialized domestic lighting product which provide a more detailed and focused range of sustainable benefit categories for consumers.

A novel up-to-date eco-design method to eco-design lighting products has been developed and used base on the integration of specific eco-design tools such as eco-design guidelines, regulations/directives, LCA software-based tools, testing tools and light analysis tools at a specific time during the design and development process. The designed lighting products present particular ‘environmental impact patterns’ in specific life cycle stages and components, and also require specific types of methods, tools and eco-design strategies to assess their environmental impact, and reduce/eliminate these impacts.

The case studies by applying environmental LCA reported in this thesis clearly demonstrate that the implementation of the framework, method and toolkit by a domestic LED table lamp, supports the decision making for engineers to move towards a more environmental friendly of lighting product development which combine resource efficiency that could be used to demonstrate the company’s sustainability responsibilities on business activities. Although the results of this research have advanced the understanding and application of environmental and social LCA assessment benefits within sustainable product development, clearly a number of additional areas which require further investigation as highlighted in the Future Work section of this chapter.

SLCA was adopted in this thesis to elaborate the scope of LCA to social impacts, whilst still an emerging area of research, it remains focused mainly on the damage impacts of the product associated with its manufacture and disposal phases, and uses the functional unit as the basis of comparative studies in the lighting product sector. Through the materiality analysis, it was identified the Access to material resources (local community), Health and Safety (consumers), fair salary (workers) and contribution to economic development (society) are among the subcategories with a high significance for ONA in relation with the product analysed. In addition, they have also identified the access to material resources (local community) and Health and Safety (consumers) as relevant subcategories with a high influence on stakeholders’ perceptions of the product.

10.3 Further work

Development of the decision-making model within the integrated eco-design approach

The integrated eco-design approach that has been developed and followed should be described and formalized in a step-by-step decision-making model in further research. This model should demonstrate how to guide users to understand the life cycle of the lighting product and make feasible decisions. The descriptive model should then be transformed into a prescriptive process framework indicating the product designer how to proceed at each step of the process.

Considering the impacts from the use phase

A drawback of the methodology is the limited assessment of the use phase in the environmental and social LCA studies. To encourage the company to apply the analytical results into the business practices, it would be beneficial for complemented with an extensive analysis of the use phase in the LCA studies. That would enable the promotion of the potentially positive social aspects of a product in this life cycle phase.

Development of weighting factors for SLCA

In an SLCA, there is a wide range of social impacts to consider, measured by quantitative, qualitative or semi-quantitative indicators, mixing positive and negative impacts. In addition, there is a demand to weight the impacts in different ways, which has been identified in the literature review phase. A possible approach for handling this might be to use multi-criteria decision analysis, which provides techniques for weighing a range of different criteria in a structured and transparent way. Using this approach would enable decision makers to express and be transparent about their values in prioritising among the subcategories.

Development of decision-making approach for applying the environmental and social LCA results into the practices of sustainable product development

Linking to environmental and social LCA results into the sustainable development is a trend. The development of social LCA needs to be linked to the simultaneously on-going development of environmental LCA, the objective of which is to integrate these two approaches somehow into a wider sustainability assessment. In order to make the approach available for common use, the development of a computer aided tool capable of supporting this possible approach at a process and data input/calculation level.

Appendix

Appendix 1 A list of guides and regulations relevant to the UK

Lighting Regulations/Guides	Comments
CIBSE code for lighting 2002	Provides practical guidelines for lighting in a range of environments.
European Standard EN 12464-1 (BSI 2002)	Provides standards adopted by 20 European countries. For the UK, this would be BSI 2002. It specifies lighting requirements for indoor workplaces with respect to visual comfort and performance. Tends to correlate very closely to CIBSE code for lighting.
CIE (Commission Internationale de L'Eclairage or International Commission for Illumination)	Guidelines and recommendations for lighting for various indoor environments and lighting design can be found.
PART L2A 2010: Conservation of fuel and power (New buildings other than dwellings	Artificial lighting efficacy targets: 55 lm/W or higher (for general office lighting)
BS EN12464: 1	Lighting for workplaces.
BS 5266	Emergency lighting.
BS EN15193	Energy Performance of buildings. Out of this standard, a measure of performance has been developed called LENI.

Appendix 2 A list of environmental LCA 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 346 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).

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.

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.

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.

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